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Development of the Mechanical Subsystems for an On-line 3D Optical Granulometry System

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Helsinki, 10.1.2016
Supervisor: Professor Kalevi Ekman
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ABSTRACT OF THE MASTER'S THESIS

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This thesis presents the process of designing the mechanical structure for a commercial particle size analyzer of granular material based on on-line 3D optical granulometry technology. The analyzer can be used to monitor and increase the performance of various processes within the mining, mineral, and metal industry (MMMI), particularly grinding processes that utilize autogenous and semi-autogenous grinding mills. The analysis system contributes to the evolution of the MMMI in a more energy efficient direction, resulting in a decreased ecological footprint of the industry as well as financial benefits for the operators. The design work done for this thesis contributes to a product development project by Outotec, a technology company specializing in the MMMI. Prior work within the project included a detailed business analysis and software development.

A systematic methodology to carry out the design work was derived from the field of engineering design literature. The methodology is based on decomposition of the design problem into smaller subproblems. By finding solutions for each subproblem individually, an overall conceptual solution is produced. This methodology was used to create explicit engineering parameters and a conceptual solution for the mechanical structure of the product, based on the prior work done on the product development project. The conceptual solution was then defined further into a complete mechanical design and a functional prototype. The prototype was tested and evaluated based on the engineering parameters. Based on the results, a second iteration of the design was created, improving on the initial design.

Based on objective evaluation of the second design iteration, the design meets all the criteria set for the product development project and can be taken to market. However, the evaluation and further iteration of the design will continue after product launch based on customer feedback and product performance.

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Tämä diplomityö esittelee optiseen 3D granulometriateknologiaan perustuvan kaupallisen partikkelikokoanalysaattorin mekaanisen suunnitteluprosessin. Analysaattorin pääasiallinen käyttötarkoitus liittyy kaivosteollisuuden erinäisten prosessien monitorointiin ja ohjaukseen. Ensisijainen käyttökohde on autogeenisiä ja semiautogeenisiä myllyjä hyödyntävien jauhatusprosessien syöttömateriaalin monitorointi. Suunniteltu laitteisto edistää kaivosteollisuuden kehittymistä energiatehokkaampaan suuntaan ja siten toimialan aiheuttaman ekologisen jalanjäljen pienentämistä. Laitteen tarkoitus on myös tuottaa taloudellista hyötyä sekä kaivosteollisuuden operaattoreille että laitteen toimittajalle. Tämän diplomityö on tehty kaivosalalla toimivan teknologiayhtiön, Outotecin, toimeksiannosta ja edesauttaa erästä yhtiön tuotekehitysprojektia.

Suunnittelutyö toteutettiin tuotekehitykseen liittyvästä kirjallisuudesta löydettyjä systemaattisia menetelmiä hyödyntäen. Käytetty suunnittelumetodiikka perustuu suunnitteluongelman jakamiseen pienempiin osatekijöihin. Suunnitteluongelma ratkaistaan löytämällä kullekin osatekijälle toimiva ratkaisu. Kyseiseen metodiikkaan sekä tuotekehitysprojektin aiempiin työpanoksiin perustuen tuotteelle luotiin yksikäsitteiset suunnitteluparametrit sekä mekaaninen konsepti. Konseptin pohjalta suunniteltiin tuotteen mekaaninen rakenne ja rakennettiin toimiva prototyyppi, joka testattiin aiemmin luotujen suunnitteluparametrien perusteella. Tulosten perusteella tuotteesta suunniteltiin toinen versio, jossa korjattiin testauksessa havaittuja puutteita.

Toisen tuoteversion objektiivisen arvioinnin perusteella suunnittelutyön tavoitteisiin on päästy. Tämän arvion perusteella tuote täyttää kaikki sille asetetut kriteerit ja se voidaan viedä markkinoille. Tuotteen suorituskyvyn arviointi ja rakenteen iterointi jatkuu kuitenkin vielä markkinoille viennin jälkeen.

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Avainsanat: Konetekniikka, koneensuunnittelu, tuotekehitys, optinen granulometria

Foreword

The work done for this thesis directly contributes to a product development project launched by Outotec, with the goal of an official product launch during early 2016. It has been a great motivator knowing that the efforts I put forth during the making of this thesis won't just end up forgotten on a library shelf or a dusty warehouse. It gives me great satisfaction knowing that the product I helped create could give a contribution, however small, to decreasing the ecological impact of mankind on the natural environment, as well as the economic growth of Outotec and the Finnish nation during these trying times. I have realized with great pleasure that I can use the skills and knowledge gathered during my years of studying mechanical engineering to the benefit of someone other than myself.

I would like to thank all of my friends and coworkers at Outotec for your help and support during the making of this thesis. A big thank you goes to all my friends and family for supporting me during the making of this thesis as well as my previous academic and non-academic endeavors. Finally, a special thank you to Emily Simonds for your support, proofreading, and helping me with the theoretical aspects of engineering design, Valtteri Mikkola for your assistance with the thermodynamic calculations, and my instructor Pertti Saviranta for all the help, support, and guidance along the way.

Helsinki 10.1.2016

Aki Laakso

Table of Contents

Abbreviations

MMMI	Mining, mineral, and metal industry
AG mill	Autogenous grinding mill
SAG mill	Semi-autogenous grinding mill
ACT	Advanced Control Tools
BR	Business (product requirement list category)
PC	Product Compliance (product requirement list category)
UR	Usability and User (product requirement list category)
ER	Environment (product requirement list category)
TR	Technical (product requirement list category)
BOM	Bill of Materials
HOQ	House of Quality
TEC	Thermoelectric cooler
COP	Coefficient of Performance
CAD	Computer aided design

1 Introduction

This thesis aims to develop a novel product based on the on-line 3D optical granulometry technology. The benefit of the product for the user is to increase the energy efficiency of processes related to the Mining, Minerals, and Metal Industry (MMMI). The product is particularly aimed at increasing the efficiency of ore grinding processes in mineral concentration plants that use autogenous and semi-autogenous grinding mills. This thesis pertains to a product development project launched by a Finnish technology company, *Outotec*. The project and the upcoming product were given the name *RockSense*.

1.1 Motivation

Although often hidden from people's daily lives, the MMMI is a major part of the global industry sector. Metals produced by the MMMI are present in many consumer products as well as professional equipment. However, the industry is founded on exploiting the earth's exhaustible resources and is known to be a very energy intensive one, leaving a large ecological footprint. Due to regulation from governing bodies and financial motivators, the technology used in the MMMI strives to evolve in a more energy efficient and environmentally friendly direction. This thesis aspires to assist this evolution by contributing to the development of a product that enables a more efficient operation of mineral processing facilities. From a financial point of view, the product benefits both the customer and the provider. The customer can achieve great financial benefit due to more efficient operation resulting in reduced costs, while Outotec can create profit through equipment sales and maintenance services. Although the motivations for the product development project that this thesis pertains to are primarily economical, the end result should lead to a decreased impact on the natural environment.

1.2 Objective

The main objective of this thesis is to develop the physical structure of the on-line 3D optical granulometry system in a level of detail where it can be added to Outotec's product portfolio and taken to market. This includes a complete mechanical design, including manufacturing and assembly documentation and a complete supply chain definition. Particularly the mechanical design process is described and other design aspects such as software development and electrical design are only briefly presented.

The RockSense project was launched years prior to commissioning this thesis and a considerable amount of resources had already been invested into a detailed business analysis and conceptual development. However, the concept design work had focused primarily on software development, and few resources had been allocated for mechanical design. This thesis was commissioned by Outotec with the purpose of producing a physical structure that could meet all product requirements and fulfill the customer needs defined for the RockSense system.

A systematic and suitable design methodology is derived from the vast field of engineering design literature. The product development process is carried out according to the chosen methodology, although the design steps will be held under constant critique and the possibility to deviate from the roadmap set by the methodology is maintained throughout the project.

The thesis objective can be divided into the following sub-objectives:

- Definition of explicit design parameters and evaluation criteria

- Review of product development literature and specification of a systematic product development methodology suitable for the RockSense project
- Detailed conceptual and mechanical design of the product
- Evaluation of the resulting design

1.3 Structure

This thesis is structured in a linear fashion, although it is important to note that the actual process behind its creation did not necessarily follow the sequence in which it is presented here. A successful product development process generally requires multiple design aspects to be considered simultaneously, making a linear design approach difficult. For the sake of clarity for the reader, this thesis is structured in a sequential fashion that enables explaining the causation behind various stages of the process.

Chapter 2 provides technical background and detailed motivation for this thesis by presenting the optical granulometry technology and its usage in the MMMI. In order to clarify the starting point of this thesis, the prior work it builds upon, and the specific goals and requirements of the product development process it pertains to, the most essential developments of the RockSense project that occurred prior to this thesis are described in chapter 3. In chapter 4, the process of selecting a systematic product development methodology and using it to analyze and deconstruct the crux of the design problem is presented. The conceptual solution for the product and the design process resulting in it are described in chapter 5. Chapter 6 presents the mechanical design process, in which the conceptual solution is explicitly defined and materialized in the form of a functioning prototype. In chapter 7, the design is reviewed and a second design iteration is presented. Chapter 8 includes a review and discussion of the design outcome and the process behind its realization, as well as suggestions for future work.

2 Optical granulometry

During this thesis, the term *optical granulometry* will refer to the process of measuring particle size distributions in granular material based on optical techniques such as 2D or 3D imaging. The process includes creating a digital image of the granular material and using various photoanalysis techniques to identify individual particles in the material and to estimate their sizes.

This chapter will give an introduction to the optical granulometry technology and its use in industrial applications with a focus on the mining, mineral and metal industry (MMMI). Detailed descriptions of the software and algorithms related to optical granulometry are however beyond the scope of this thesis.

2.1 Technology overview

Particle size analyses have great importance in industries that handle large quantities of materials with variable particle sizes, such as the MMMI, materials handling, forestry, and agriculture. For instance, in the materials handling industry sizing measurements can be used to reduce delays and congestion in loading and transport caused by the excess of particles that are too big or too small to meet process specifications. [1] The usage of optical granulometry in the MMMI will be discussed further in section 2.2.

Optical granulometry methods offer many advantages over traditional particle sizing methods such as sieving or screening. Image based analysis is very quick, inexpensive and practical in comparison. Large quantities of material can be processed quickly and many samples can be analyzed, which makes sampling errors less significant. Unlike screening or sieving, optical granulometry methods are not limited by the size or quantity of the particles and due to their speed and non-contact nature, they do not interfere with the production process or damage the material. [1]

The first optical granulometry systems were based on an off-line approach, where operators would use handheld cameras to take pictures or video of material piles to be analyzed later, as shown in Figure 1. This approach can result in a lot of sampling errors and it was later recognized that a better way for imaging-based size measurement is an on-line approach where material moving on a conveyor belt or falling off the end of a conveyor belt is analyzed, as seen in Figure 2. [2] Although manual photographic analysis methods have been used in the past, nowadays photoanalysis software and machine vision techniques are used to automate the process. On-line optical granulometry equipment combined with modern computing and machine vision technologies can produce results in real time, enabling effective process control and monitoring.


Figure 1: Off-line optical granulometry approach [2]


Figure 2: On-line optical granulometry approach [3]

2.2 Usage in the Mining, Mineral and Metal Industry

The process of mining minerals from the earth and refining them into metals and other valuable materials is a complicated and multifaceted process involving many stages and sub-processes. Many of these processes affect and are affected by particle size and can benefit greatly from accurate sizing measurements. For example, sizing measurements of fragmented rock are essential in evaluating explosives, blasting patterns and the accuracy of blasting simulations. The results can be used to optimize blasting parameters to reduce costs. The description of all processes within the MMMI that can potentially benefit from sizing measurements is beyond the scope of this thesis. However, the *grinding process* is one where size distribution information has particular importance [4, 5] and will be discussed in more detail.

The process of extracting valuable materials from the earth begins with *comminution*. The term comminution is synonymous with size reduction and refers to the process of breaking large bodies of minerals such as boulders and bedrock down to small particles. The purpose of comminution is to break apart and separate the various mineral particles from each other so that the valuable minerals can be separated from unwanted material. The comminution phase typically involves three stages: blasting, crushing, and grinding. Each stage breaks the material down to smaller particles, typically resulting in a particle size of around 10-500 micrometers after the grinding stage. The comminution process is illustrated in Figure 3. [6]

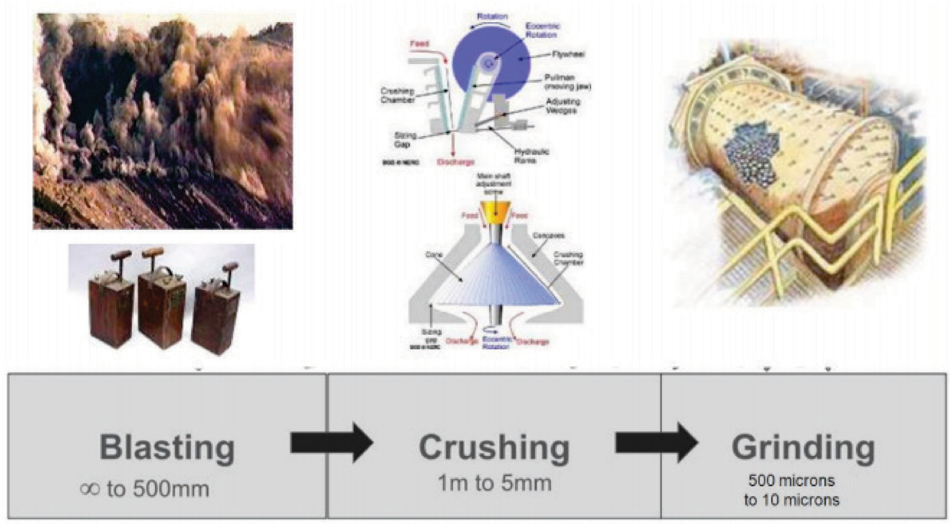


Figure 3: Illustration of the comminution process [6]

The most common type of grinding machine is a tumbling type grinding mill, in which the ore is lifted by a rotating cylinder and thrown back down as illustrated in Figure 4. Grinding media such as steel or ceramic balls or steel rods can be added into the mill to enhance the grinding process. Mills that do not require additional grinding media or in other words, can use the ore itself as grinding media, are referred to as autogenous mills (AG mills). Some mills use a combination of ore and additional material as the grinding media. These mills are called semi-autogenous mills (SAG mills). Other types of grinding machines include stirred mills, vibrating mills, and grinding rolls. [6]

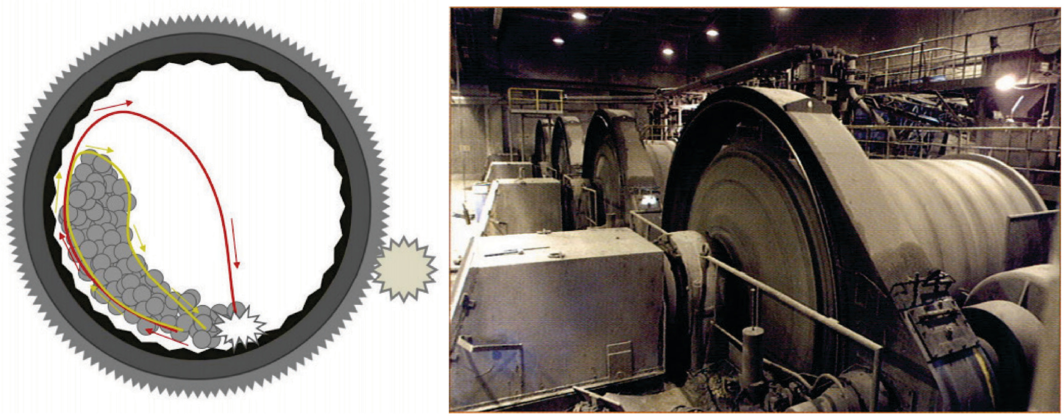


Figure 4: Operation principle of a tumbling type grinding mill (left) [6] and grinding mills at Pyhäsalmi mine in Finland (right) [4]

The grinding process is an extremely energy intensive one, so there is great potential for cost reduction in effective optimization of the mills. High performance and energy efficiency in AG and SAG mills can be achieved either by optimizing the size distribution of the granular material being fed into the mills, or using additional grinding media [4]. Online optical granulometry technology can be used to monitor the size distribution of material moving from the crushers to the grinding circuit. Monitoring the grinding mills' input material provides feedback that can be used to adjust the crushing process parameters and produce material with optimal size distribution for the grinding mills. For example, in the Porgera gold mine in Papua New Guinea, optimizing the size distribution of the grinding mills' input material resulted in a 25% increase in mill throughput. An optical granulometry system was used to monitor the crushers' output material in order to adjust the crushers' settings accordingly. [7]

Significant savings can also be achieved in the additional grinding media costs if the grinding mills' input material size distribution is optimized. Experts at Pyhäsalmi mine in Finland have estimated that 200 000 Euros could be saved annually in iron balls if correctly sized feed material were provided to their grinding mills at all times. This estimation resulted in an initiative by the mining company to develop a new optical granulometry instrument in order to monitor the grinding mills' input material and achieve the estimated savings. [4]

2.3 3D optical granulometry

There are a number of products on the market that can measure size distributions of granular material moving on a conveyor belt. Most of these products are based on photographic 2D imaging. Machine vision software is used to process the images, identify individual particles, and estimate size distributions. An example screen capture from the Split-Online® imaging system is shown in Figure 5. [4]

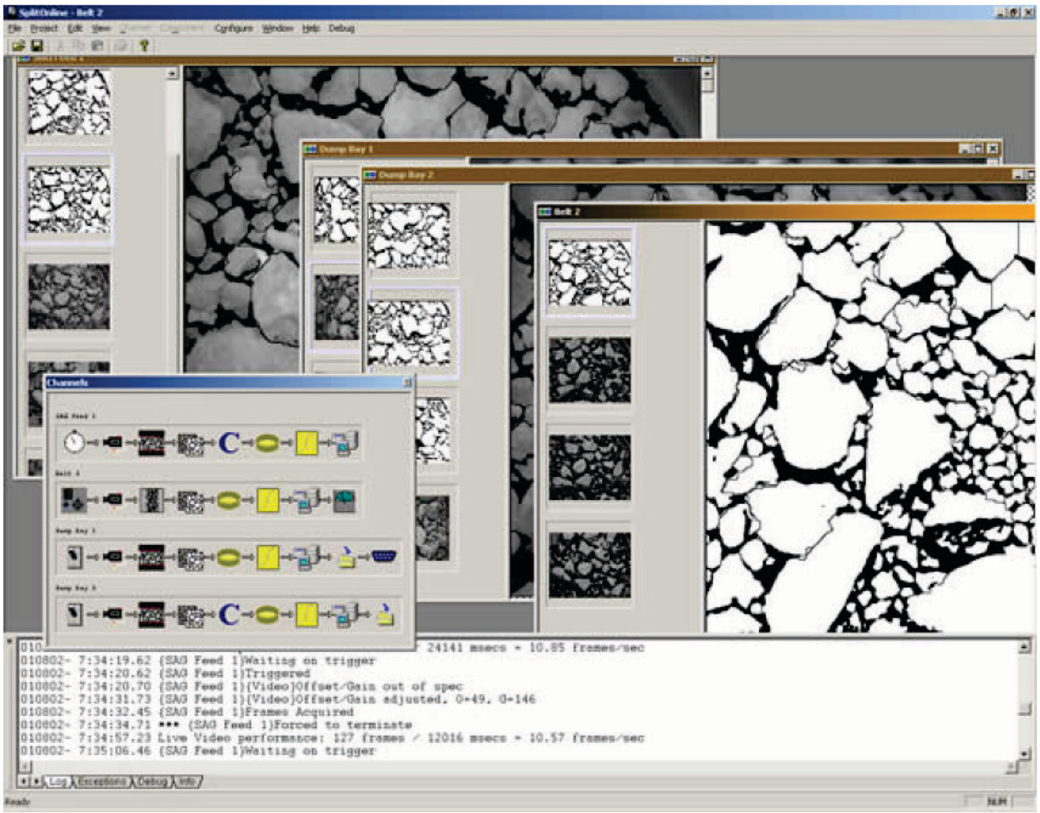


Figure 5: Example screen capture from the Split-Online® 2D optical granulometry system [4]

While optical granulometry methods based on photographic 2D imaging can produce useful results, there are significant sources of error related to these techniques. Systems based on 2D imaging are subject to significant *particle delineation error* caused by shadows, uneven lighting conditions, and color variations in the material. Particle delineation error refers to inaccuracies in identifying the edges of different particles and estimating their shapes and sizes. 2D imaging systems also have no direct measure of scale, are subject to perspective distortion, and cannot distinguish between overlapped and non-overlapped particles. Furthermore, 2D systems tend to group areas of fine particles as large regions, and clusters of mid-sized particles as large rocks. [8]

Due to the limitations of 2D optical granulometry technology, 3D imaging has been looked into as a better basis for particle size measurement in numerous publications including Thurley [8], Kaartinen [4], and Lee et al. [9].The advantages of 3D over 2D imaging include elimination of particle delineation errors caused by shadows and color variations in the material, the ability to identify overlapped and non-overlapped particles and areas of fines, and the ability to estimate particle volumes [8]. Kaartinen [4] and Thurley [8] present 3D imaging based methods that can accurately measure the size distributions of granular material.

3 The RockSense project

As chapter 2 points out, operators in the mining, mineral and metal industry can potentially achieve great financial benefit with on-line 3D optical granulometry technology, particularly by using it to monitor and optimize the feed material for AG/SAG grinding circuits. Having discovered this potential, Outotec launched a product development project aspiring to bring the technology to the market. The project and the upcoming product were given the name *RockSense*. The project goal is to develop and bring to market a novel on-line particle size analyzer based on the 3D optical granulometry technology. The primary application of the product will be monitoring the grinding process feed material but other uses such as blast fragmentation monitoring are also possible.

This thesis was commissioned by Outotec as a part of the RockSense project, and particularly the product development stage of the project. In order to clarify the context, starting point, and motivation of this thesis, an overview of the RockSense project as a whole is provided in this chapter. It is important to note that the processes and decisions described in chapter 3 were not directly related to the design work presented in this thesis, but rather were a part of the prior work this thesis builds upon. The descriptions focus on presenting the outcomes and deliverables that are relevant to this thesis.

3.1 Roadmap

The RockSense project follows Outotec's internal product development model that is based on a *stage-gate product development method* [10]. The stage-gate method is a very common template in product development management and has been successfully implemented in a wide variety of organizations [11]. The stage-gate method breaks the product development process down to a predetermined set of stages, each of which consists of predefined activities aimed at advancing the project towards the final product launch. Each stage is preceded by a decision gate, a checkpoint where the project is evaluated and a go/cancel decision is made. The stage-gate method provides the project team with a systematic approach to carry out the project goal and enables objective evaluation at each gate. Since the costs for a product development project tend to escalate as the project advances, frequent checkpoints can prevent resource allocation to unprofitable endeavors [11]. Additional advantages include good communication with project stakeholders and quick speed to market. The stages in Outotec's adaptation of the stage-gate method and their corresponding gates are illustrated in Figure 6. [10]

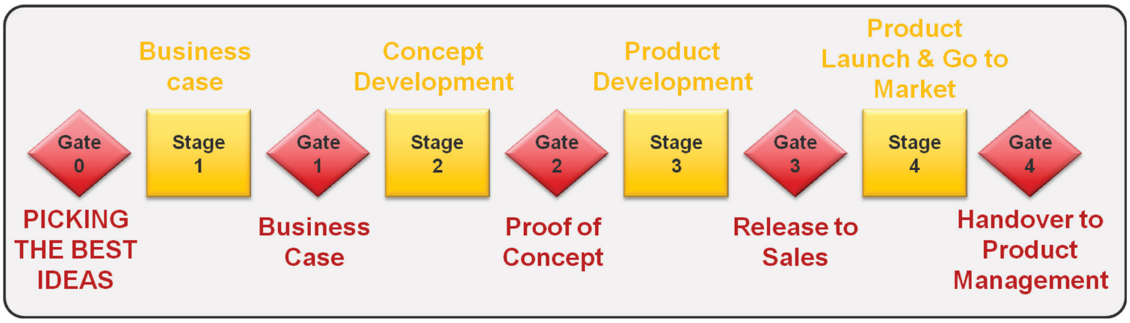


Figure 6: Stages and gates in Outotec's product development model [10]

Each stage is carried out according to a predetermined plan with the intention to advance the project and to decrease the uncertainty and risk involved in the decisions being made in the following gate. A brief explanation of each stage and their essential contents is given below: [10]

Stage 1: Business Case
- Detailed business analysis including competition analysis, profitability estimation, risk analysis etc.

Stage 2: Concept Development
- Definition of customer needs and product requirements
- Identification and analysis of solution alternatives
- Selection and validation of the most suitable alternative

Stage 3: Product Development
- Detailed design, development, and validation of the new product
- Definition of supply chain and delivery capabilities

Stage 4: Product Launch and Go-to-Market
- Commercial launch
- Validation of the final design
- Post-launch review

The deliverables from each stage are brought to the following decision gate. The gates serve as quality control checkpoints where the deliverables are evaluated against a predefined set of success criteria that may include strategic fit, market attractiveness, competitive advantage, and technical feasibility. The outcomes of each gate should include a decision on the continuation of the project and an approval or rejection of the plan for the following stage. [10]

3.2 Business case

The business case stage attempts to define the product in terms of the benefit it provides to the customer and the features that should be offered. The attractiveness and profitability of the product as well as its fit within the company strategy are evaluated before resources are spent on further development. This stage should define the outcome of the project and justify beginning the actual product development process. [11] In Outotec's system, the business case deliverables include definitions of customer needs and requirements, positioning strategy, market segments, earning logic, risks, and initial business goals. [10]

The exact details of the RockSense business case are both confidential and non-essential to the main topic of this thesis so the business case will be presented here in a very brief and general manner.

As previously mentioned, the primary customer business challenge that the RockSense project attempts to solve relates to optimizing the grinding circuit efficiency in mineral concentration plants by monitoring their input material. The RockSense system will differentiate from the competition by introducing 3D optical granulometry technology to a market consisting largely of products based on 2D imaging techniques. The finished product should be a complete and automatic analysis system that includes the appropriate software and mechanical equipment and can be installed and maintained with minimal operator interference. [12]

For further product differentiation, additional optional functions are offered. These functions include software modules such as mill feed control, reporting and statistics, inappropriate object detection, and belt condition inspection. The system should also be applicable in a very wide range of operational environments and customizable according to customer needs. To achieve this, optional subsystems that increase the products operational environment, such as cooling and heating modules, will be offered. The basic system price should be competitive with other products in the market. The optional functions will be sold separately. Maintenance and spare part services will be offered with the product. [12]

The main market segment providing the fastest market entry consists of existing mineral concentration plants that use AG/SAG grinding mill circuits. Other segments include greenfield projects with AG/SAG mills, mines with ball/rod mill circuits, and crushing plants. The RockSense system will complement Outotec's automation product portfolio and support the sales of other related products such as grinding mills and automation systems. [12]

3.3 Concept development

The main goal of the concept development stage is to come up with a proven conceptual solution to meet the customer business challenge. The concept's feasibility needs to be verified by prototyping or virtual modeling, for example. Another important aspect of concept development is creating a detailed list of product requirements that can be used as design guidelines in the product development stage. In addition to the proof of concept and the product requirement list, the deliverables for the concept development stage include a draft of the product's logical and functional structures and a product development plan. [10]

The particle size distribution of granular material is generally given as a *Feed value* such as F80 or F50. An F80-value of 10mm means that 80% of the material would pass through a 10mm sieve. Operators in the MMMI are particularly interested in the cumulative F-values represented as a historical trend. The RockSense system should be able to provide information about the F-values as well as volume flow and individual particle sizes of the material being analyzed. [5]

Instead of undertaking the arduous task of creating an entirely novel approach to 3D optical granulometry, the RockSense project team took the measurement system presented and proven effective by Thurley [8] as the basis for concept development. Thurley's results would also be used as a benchmark in concept validation. Thurley's method is based on a 3D imaging technique called *laser triangulation*, where a laser line is projected on the measured object and a camera at an offset angle is used to calculate its height profile. In other words, each frame captured by the camera shows the laser as a cross section of the object viewed from an angle. Because the distance and angle of the camera in relation to the laser is known, the height of each point of the cross section can be calculated. The laser triangulation method is illustrated in Figure 7.

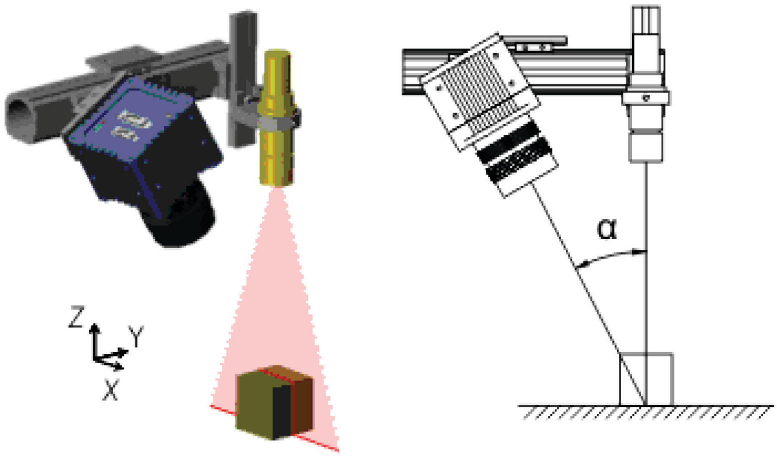


Figure 7: Operating principle of laser triangulation [13]

Thurley's method analyses the 3D profile data in three consecutive phases: *particle delineation*, *particle classification and sizing,* and *sieve-size distribution calculation*. The particle delineation phase uses various algorithmic methods to segment the granular material, i.e. identify and distinguish individual particles from one another. In the particle classification and sizing phase each segmented region is classified as an *area of fines*, a *non-overlapped particle*, or an *overlapped particle*. Each region identified as an area of fines is converted into a volume estimation based on the 3D surface profile and the depth of the material. The 3D surface profile of each non-overlapped particle is analyzed and its volume and sieve-size estimated. Estimating the size of overlapping particles is very difficult and thus they are ignored in order to avoid incorrectly sizing them as smaller particles. The sieve-size distribution is calculated based on the estimated sieve-sizes of the non-overlapping particles and the cumulative sum of all estimated volumes, including the fines. [8]

A commercial 3D imager was chosen to be used in the RockSense project. The imager is a complete system including all the equipment and software needed for 3D imaging. The imager in question was selected because it offers a wide operational environment, a robust design, and a relatively small size. The essential specifications for the chosen imager are listed in Table 1. Photographs taken of the imager can be seen in Figure 8.

Table 1: Essential specifications for the 3D imager chosen for the RockSense system [14]

Weight	7,0 kg
External dimensions (L x H x D)	420 x 163 x 107 mm
Operating temperature	0°C … 40°C
Storage temperature	-30°C … 70°C
Vibration tolerance	58…158Hz / 5G
Single shock tolerance	15G
Enclosure rating	IP65
Housing material	Aluminum
Installation height	280 – 1280 mm
Heating power	7 W

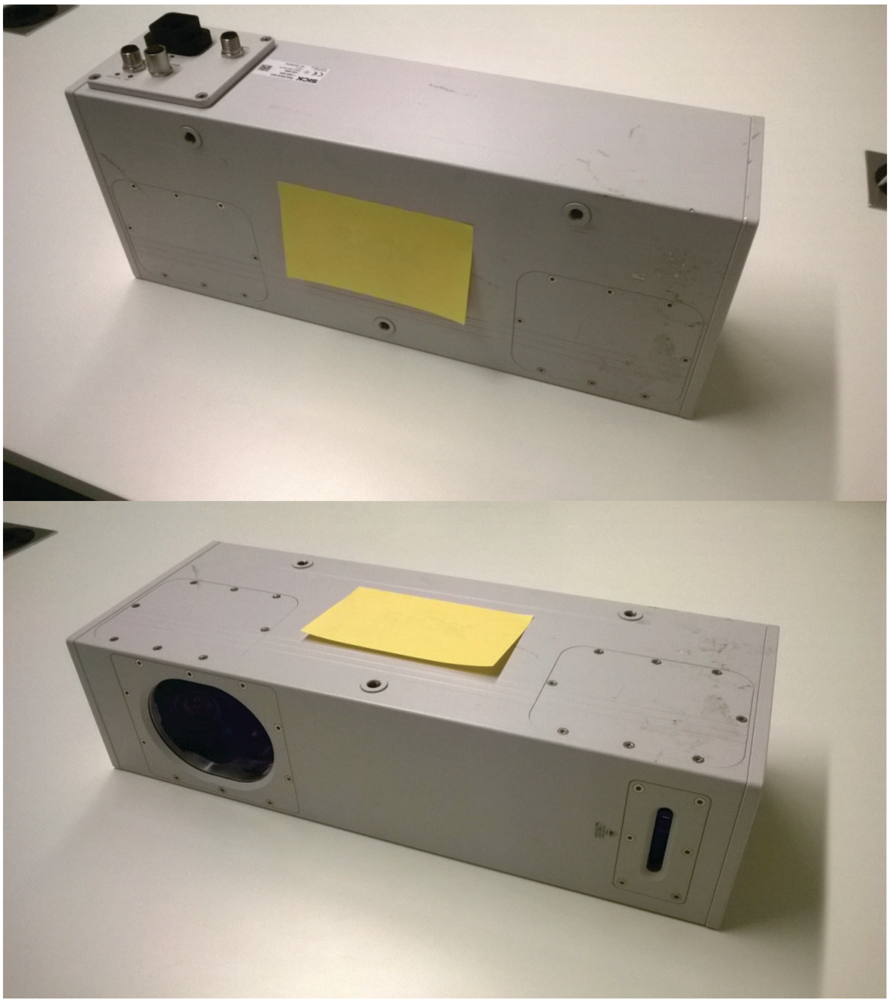


Figure 8: The 3D imager selected for the RockSense project (manufacturer information covered)

3.3.1 Product requirements

A vital part of the development process for new products is creating a precise and detailed list of requirements that the finished product should meet. These requirements specify the product's boundary conditions and make up the framework for the design process. The requirements should take into account all aspects that influence the product including operational environment, customer needs and desires, market requirements, safety standards, etc. The requirements should be simple and unambiguous and when possible, defined as explicit numerical values. In any case, the product's ability to meet each requirement should be easily observed or measured. Each requirement should be classified as *mandatory* or *optional* according to its importance to the finished product performance. Mandatory requirements must be fulfilled in any situation before the product can be considered finished, while optional requirements are additional features that may improve the product but are not absolutely necessary. [15]

The RockSense requirement list was composed in cooperation with the project team, experts in various technical fields related to the project, and operators in the MMMI. The 3D imager chosen for the project also brings about some design constraints, such as installation height, which have been included in the requirement list. As the Outotec product development guidelines dictate, the product requirement list is comprised of five main categories: Business (BR), Product Compliance (PC), Usability and User (UR), Environment (ER), and Technical (TR). In addition to the "mandatory" and "optional" classifications, a third label, *nice to have*, is used. The requirements marked "nice to have" will be kept in the design process and discarded only if they turn out to cause a lot of extra work or additional costs. [16]

The entire RockSense requirement list includes more than 60 items, many of which are not relevant to the scope of this thesis and will not be presented here. However, the requirements that are essential to this thesis are compiled in Attachment 1.

3.3.2 System functions

The basic functional structure of the RockSense system was compiled based on the requirement list and Thurley's [8] basic concept. It can be divided into two categories: hardware functions and software functions. The list of functions can be seen below:

Software functions
- Ore segmentation
- Sieve size estimation
- Histogram and F-value formulation
- Result presentation
- Communication handling

Hardware functions
- 3D imaging
- Conveyor belt speed measurement
- Imager attachment above the conveyor belt
- Protection of equipment against environmental conditions

Modern processing plants are typically run by computerized control systems, operated from a singular control room, that allow the operators to optimize all plant operations and maximize production efficiency. The server computers are kept in a centralized location away from the harsh conditions of the plant floor. The RockSense software is intended to be run on its own server computer provided with the system called the *ACT-server*. ACT stands for Advanced Control Tools, which is a general name for Outotec's automation and control solutions. [17]

The 3D imaging equipment, however, has to be installed above a moving conveyor belt inside the processing plant. This can be problematic if the imager is very large in size or weight. In order to minimize the weight and size of the imager, it was decided that the RockSense imaging hardware would be divided into two separate units: the Imager Unit and a Control Cabinet. All of the imager's support systems that do not need to be above the conveyor belt, such as power converters and communication ports, will be installed inside the Control Cabinet that will be placed in close proximity of the Imager Unit. The Imager Unit will only contain the 3D imager and the support systems that need to be inside or around its enclosure.

A close look at the requirement list reveals the requirements related to the operational environment to be quite demanding. The system must be able to operate in any temperature between -30 and +55°C. Furthermore, experiences from the operators have shown that the typical environment for the Imager Unit has a very high concentration of airborne dust particles that arise from the crushed ore material. Thus it was concluded that the Imager Unit will very likely require cooling and heating systems as well as systems that prevent dust from entering the Imager Unit or Control Cabinet enclosures and covering the imager optics.

3.3.3 Software

It was realized early on in the concept development stage that the ore segmentation algorithms would be the most crucial component of the RockSense system. Detailed descriptions of analysis algorithms have not been presented in Thurley's [8] research or other literature, which meant that most of the project resources had to be allocated to algorithm development in the concept development stage. The algorithm development was carried out mainly by subcontractors specializing in machine vision systems.

A detailed description of the analysis algorithms is not included in this thesis, but their general principle of operation is explained briefly. The analysis begins by preprocessing the images captured by the 3D imager's camera, followed by particle delineation. The particle delineation is done by a variety of complex edge detection algorithms to identify individual rocks from the granular material. An example of successful edge detection done by the RockSense software can be seen in Figure 9. The height information can be obtained from either the range data derived from laser triangulation, or the laser intensity data provided by the 3D imager. The RockSense software uses both methods in its size estimation process, although the range data has been determined more useful. The size estimation is started from the highest point of an individual rock, wherefrom the algorithm moves down, measuring the size of the rock layer by layer until the edge is reached. The cumulative information of the size estimations is then used to calculate the estimated sieve size and F-values of the granular material. [18]

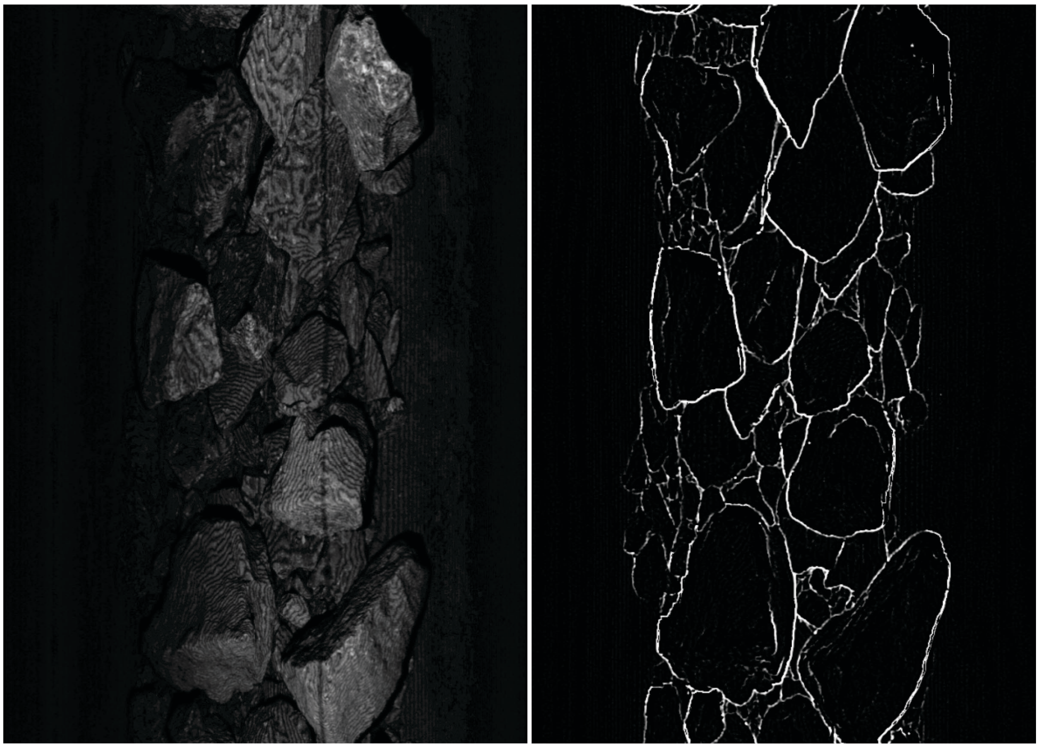


Figure 9: Example frame from the 3D imager before (left) and after edge detection (right) [18]

The software concept was validated by a laboratory test. A simple test setup as seen in Figure 10 was built, that allowed rocks and fine rock dust to be moved on a simple conveyor belt under the 3D imager. Rocks with known volumes, weights, and sieve sizes along with fine material were measured by the analysis software. The analysis results were then compared to the known values of the rocks to validate the analysis.

Figure 10: Laboratory validation test of the RockSense analysis software

In order to validate the software concept in an actual operating environment, two long term site tests were conducted in the Kevitsa mine in Finland. A simple enclosure was built for the 3D imager, which could be installed above the conveyor belts, as seen in Figure 11.

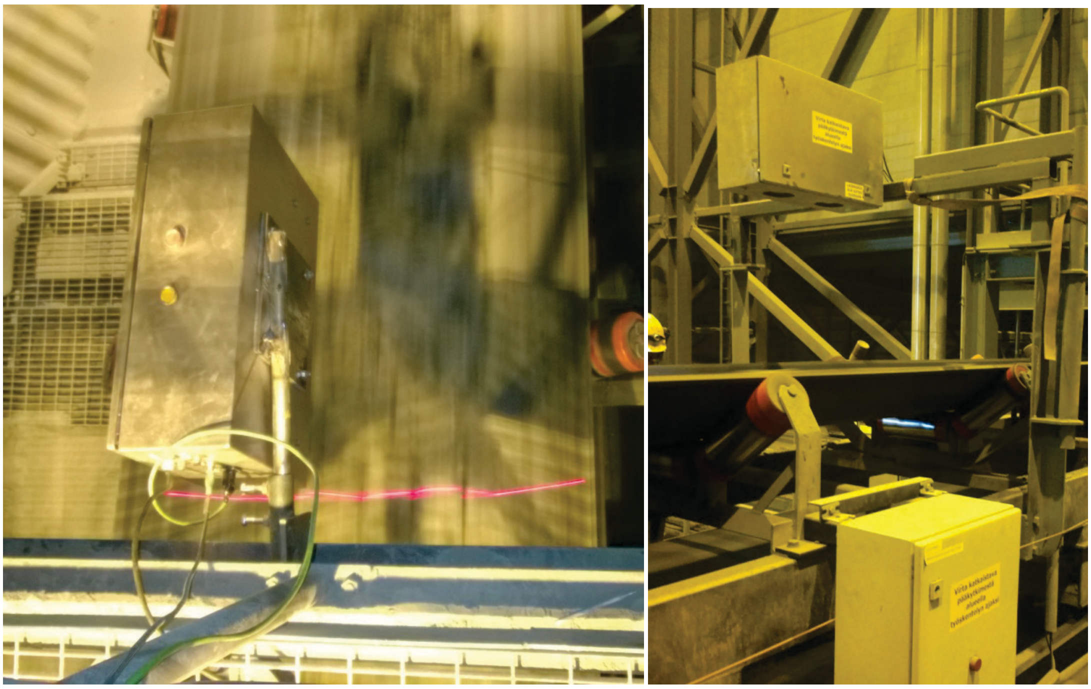


Figure 11: RockSense concept validation test installations at the Kevitsa mine [19]

The laboratory test and the site tests produced positive results, although room for improvement still existed in measurement accuracy. However, the results were sufficient in proving that the concept works and the project could be moved forward to the product development stage.

3.3.4 Hardware

A preliminary hardware concept was developed for the RockSense system during the concept development stage. The Imager Unit hardware concept was based on a sheet metal frame that could be attached to the support structures on each side of the conveyor belt, as shown in Figure 12. The 3D imager and other hardware would be installed inside a sealed enclosure that could be moved laterally along the frame for maintenance. However, after a detailed review of the mechanical concept, it was realized that the assembly would be too large for many installation sites where space around the conveyor belt is limited. Consequently, the mechanical design for the Imager Unit was to be started from scratch during the product development stage.

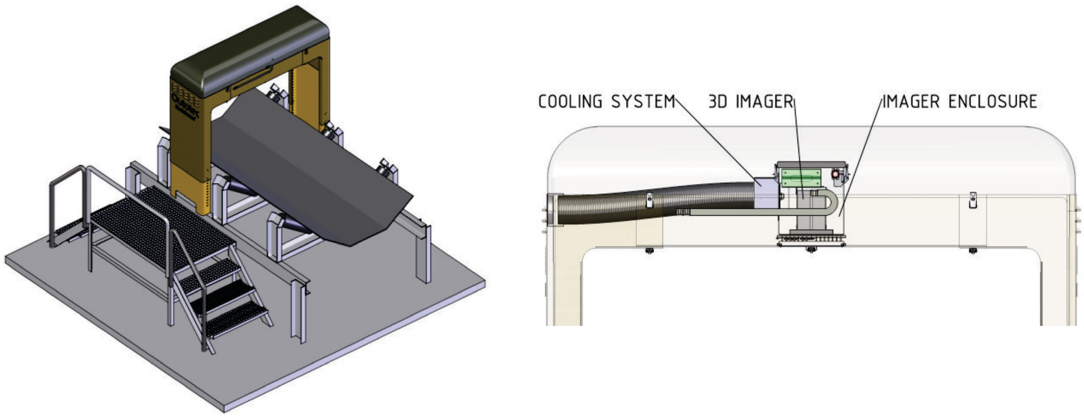


Figure 12: Initial hardware concept for the RockSense Imager Unit

The Control Cabinet design concept was based around an existing solution used in many other Outotec products. The equipment is installed inside a sealed enclosure that includes readymade flanges for wall attachments, cable throughputs, DIN rails for electronics attachment, a power switch, and a power indicator. The enclosure is shown in Figure 13. It was determined that this mechanical concept meets all the demands for the Control Cabinet and would be readily available for the RockSense system with an existing manufacturing and assembly chain. Therefore, it was decided that the Control Cabinet would not require additional design work during the product development stage, unless prompted by unforeseen circumstances.

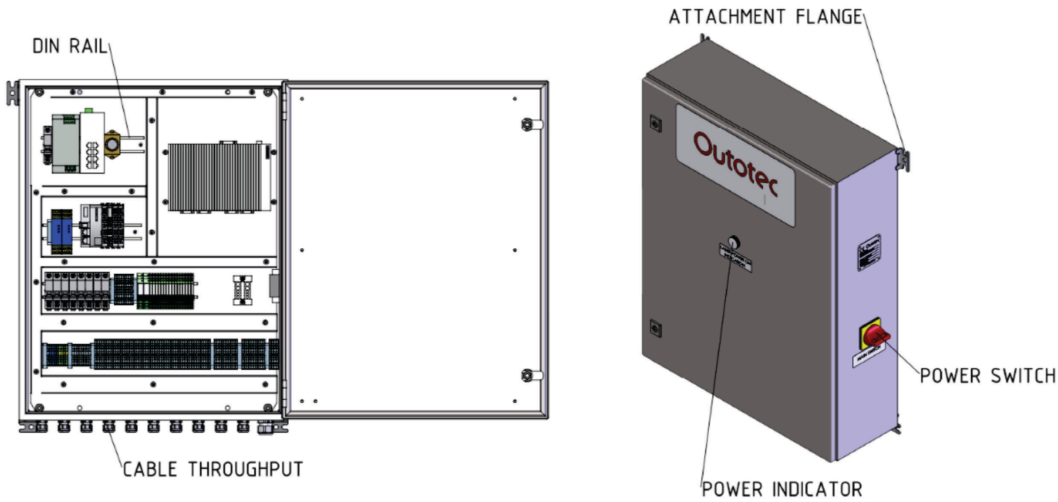


Figure 13: RockSense Control Cabinet

4 Design problem analysis

This thesis was commissioned by Outotec as the RockSense project had recently been cleared to enter its product development stage. As mentioned in chapter 3, the main focus of the concept development stage had been in algorithm and software development. This combined with the initial hardware concept of the Imager Unit turning out unsuitable resulted in a pressing need to advance the mechanical design process in order to keep the project on schedule. This thesis was commissioned in order to find the most suitable product development methods for the RockSense hardware and use of them to design its mechanical structure. Since the mechanical concept of the Control Cabinet was already designed and validated during the concept development stage, the design work described in this thesis is focused on the Imager Unit. This chapter first describes the design methodology used to undergo the design process. Then a description is given of how the methods were utilized to conduct a detailed analysis and decomposition of the design problem, and to define explicit design parameters to be used as guidelines for the mechanical design process.

4.1 Design methodology

Outotec's stage-gate model merely provides the required outputs and deliverables for the product development stage and does not comment on any practical means to achieve them. Instead of taking a completely intuitive design approach, literature in the field of engineering design and product development was looked into in order to find a structured and systematic methodology with which to carry out the mechanical design process. A systematic design approach provides a concrete course of action for the designer by structuring the essential design problem into simple working steps and design phases that can be adapted according to the specific task. Rather than hindering the designer's intuition, creativity and experience, an effective design methodology should foster and guide them while enabling an objective evaluation of the design outcomes. [15]

Pahl, Beitz et al. [15] present a systematic design approach that can be regarded as a cornerstone in engineering design literature. This approach was chosen to be used as the foundation for the design decisions made in this thesis due to its well established reputation in the engineering design community as well as previous positive experiences with its implementation. However, as the authors themselves point out: "what is learned and recognised about design methodology should not be taken as dogma" [15]. Therefore, the option to deviate from the chosen design methodology or to supplement it with additional literary sources will be considered when needed. The methodology presented by Pahl, Beitz et al. [15] will from now on be referred to as the *Pahl & Beitz methodology* during this thesis.

The basic structure of the Pahl & Beitz methodology is illustrated in Figure 14.

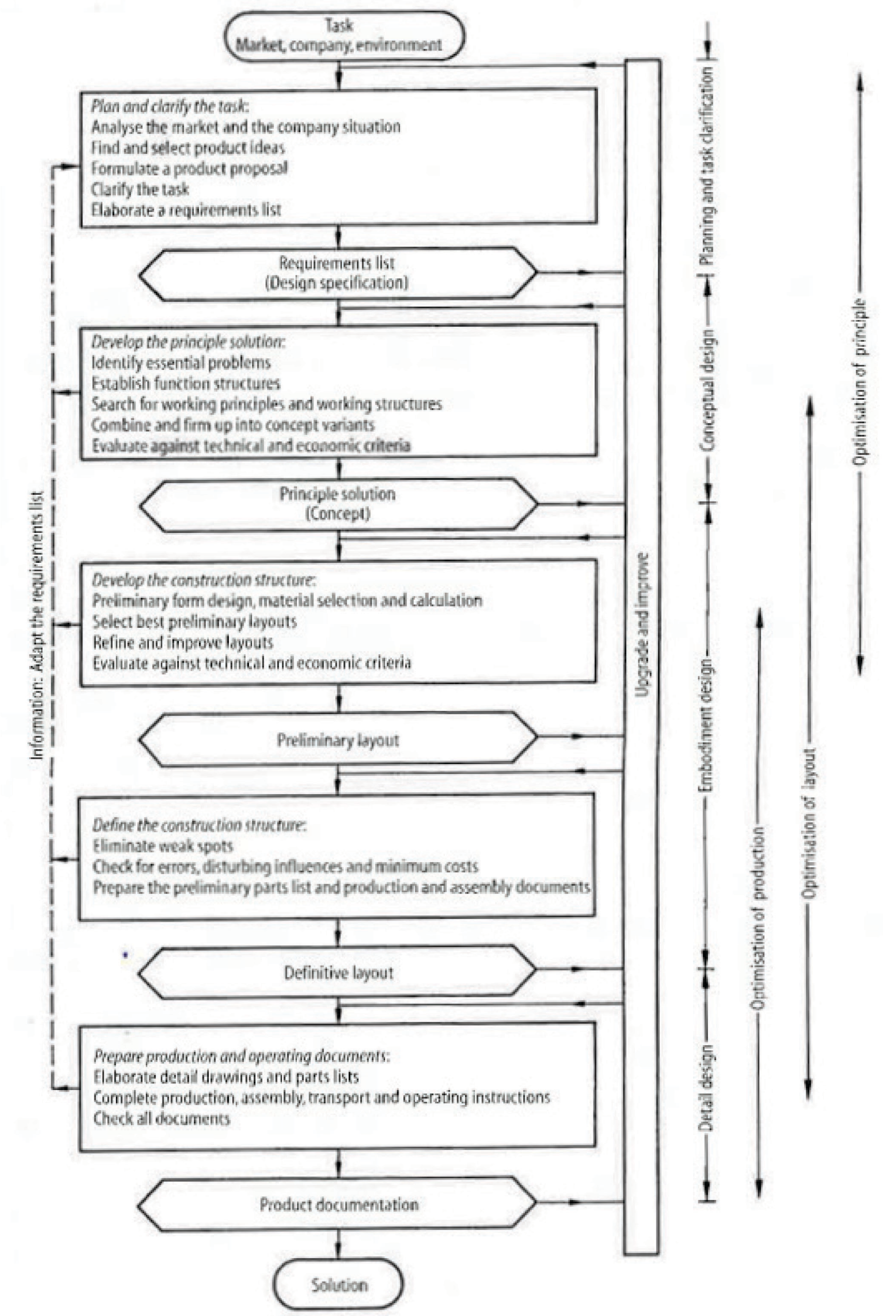


Figure 14: Basic structure of the Pahl & Beitz methodology [15]

Much like the stage-gate model adapted by Outotec, the Pahl & Beitz methodology is begun by performing a detailed analysis of the business case and customer requirements followed by concept generation, evaluation and selection. The chosen concept is then refined further and constructed into a functional layout and finally a detailed embodiment design. The design is then optimized further in terms of production costs, materials, and product documentation. Each phase in the design process includes detailed steps and techniques designed to advance the project forward in a systematic manner, although the process includes frequent evaluations and is often iterative and parallel rather than strictly sequential. [15]

As described in chapter 3, some design work related to the RockSense Imager Unit been completed already before this thesis was commissioned. However, since the concept development stage in the RockSense project focused primarily on software development, some of the design parameters defined earlier would require further specification.

4.2 Engineering design specification

The most important output from the concept development stage in terms of mechanical engineering is the product requirement list, since it defines the explicit goals and boundary conditions for the design. A close look at Attachment 1 reveals that, while helpful, the requirement list for the RockSense system does not define the product as explicitly as is necessary to reach a satisfactory design outcome. Most of the requirements related to mechanics are quite subjective, which leaves them open to interpretation and makes defining design parameters difficult. For example, accomplishing the requirement "Equipment is easy to move to the site: size, weight, handgrips, packing etc." cannot be explicitly evaluated.

Compiling an entirely new requirement list according to the Pahl & Beitz methodology would require extensive research into customer needs by conducting interviews, surveys, and observations. Instead, a decision was made to modify the initial requirement list into a form that is more useful for mechanical design. This would be accomplished by first interpreting the initial requirements as raw customer data and formulating them into explicit customer need statements and engineering metrics. Any information gaps contained in the initial list would be supplemented by the vast knowledge base accumulated by the project team during the earlier stages of the RockSense project. A simple and systematic approach presented by Ulrich and Eppinger [20] was used as a guideline during this process.

First the fundamental customer needs were recognized by transforming the requirements from the initial requirement list into customer need statements that answer the question: "what does the customer need?" According to Ulrich and Eppinger [20], the statements should be expressed in terms of *what* the product has to do, as opposed to *how* it might do it, with the same level of detail as the raw data. Preferably the statements should also state what the product *does* instead of what it *should not do*. After compiling the list of customer needs, an analysis of their relative importance to the customer needs to be conducted.

The customer in this case was defined as a typical mineral concentrator plant operator who would benefit from using the RockSense system to optimize their grinding circuit efficiency. As a result of the process described above, customer need statements were recognized as listed in Table 2. For simplicity, the needs were organized into clusters of related needs. Furthermore, each need statement was given a numerical value based on its perceived importance to the customer with 10 representing a crucial need and 1 a redundant need.

Table 2: Customer need statements

Need Clusters	Customer need statements	Importance
Low Cost	The Imager Unit is priced similarly to competitive 2D imagers	8
Compact size	The Imager Unit can be carried to the installation location without additional equipment (e.g. forklift)	5
	The Imager Unit takes up a little space at the installation site	6
Easy Maintenance	The Imager Unit enables replacing the 3D imager quickly and easily	5
	The 3D imager's optics can be cleaned without having to open the Imager unit	3
	The Imager Unit can be taken down for maintenance without causing a production stoppage	5
Easy Installation	The Imager Unit can be installed without causing a production stoppage	5
	The Imager Unit can be installed without special equipment or expertise	6
Reliability	The Imager Unit requires infrequent maintenance/can go long periods without maintenance	6
Robustness	The Imager Unit is robust against dust, humidity and extreme temperatures	9
Adaptivity	The Imager Unit can be installed above conveyor belts with varying support and cover structures	10
	The Imager Unit can operate without a water supply	6
	The Imager Unit can operate without a pressurized air supply	6
	The Imager Unit can be customized according to the customer's special needs	9
Optional functions	The Imager Unit enables video surveillance for additional information and feedback	6
Safety	The Imager Unit does not expose personnel to the risk of eye damage	9

While the customer needs statements describe the objective of the product accurately, they provide little specific guidance for the engineering process. Therefore, more detailed and explicit functional parameters would need to be established based on the customer needs statements. The resulting parameters could be called product requirements, but in order to differentiate them from the initial RockSense product requirements, they will be referred to as *engineering metrics* during this thesis. An effective way to establish the engineering metrics is to consider each customer need individually and contemplate what explicit and measurable attribute of the product would best describe whether or not the need is met [20].

Target values for each metric were given based on the initial requirement list and input from the RockSense project team experts. The resulting list of engineering metrics is shown in Table 3.

Table 3: Engineering metrics

Metric	Unit	Target value
Bill of Materials (BOM) cost	€	Confidential
Total mass	kg	25
External dimensions	mm	600x500x400
Time to replace the 3D imager	min	15
Operation time	%	95
Standard maintenance interval	months	6
Maximum operational environment temperature	°C	55
Minimum operational environment temperature	°C	-30
Protection against intrusion (dust, water etc.)	IP rating	IP66
Installations possible without modification	%	80
Optional video camera installment	yes/no	yes
Laser safety standards SFS-EN 60825-4 and SFS-EN 12254 are met	yes/no	yes
Requires water supply input	yes/no	no
Requires pressurized air input	yes/no	no

In order to determine the relative importance of the engineering metrics, a *House of Quality* (HOQ) matrix was created as seen in Attachment 2. Creating the House of Quality involves analyzing how the customer needs relate to the engineering metrics and how the metrics relate to each other. It also requires estimating the difficulty of reaching the target value for each metric. As a result, the House of Quality yields a numeric value for each engineering metric that represent their importance in fulfilling the customer needs. These values can be used to guide the design process and prioritize some engineering metrics over others in situations where compromises are necessary.

According to the House of Quality matrix, the three most important engineering metrics of the RockSense Imager Unit are *installations possible without modification*, *operation time*, and *maintenance interval*. These metrics are followed by *protection against intrusion* and the operational environment temperature metrics.

Ideally the House of Quality would also include an analysis of competing products. Unfortunately, products in the optical granulometry field are generally sold directly to the customer and proprietary information about them could not be obtained. Therefore the competitor analysis was omitted from the House of Quality analysis.

4.3 Functional decomposition

Many design problems are too complex to be solved as a single entity. It is often beneficial to divide the problem into more manageable subproblems that can be solved individually. The division is to be done in a way that enables the overall design to be solved as a collection of smaller designs. [20] This principle was applied in the conceptual design of the Imager Unit. The basic function of the Imager Unit was divided into smaller subfunctions. Finding a conceptual solution for each subfunction would produce the overall conceptual design, as seen in chapter 5.

The problem decomposition process was started by first defining the crux of the design problem. When creating novel designs, it is important for the designer to distance themselves from their previous experiences, prejudices and conventions that might influence design decisions. *Abstraction* is a technique commonly used to identify the crux of the task and prevent biases towards preconceived solutions. Abstraction means broadening and generalizing the problem formulation until an objective is reached that leaves all possible solution alternatives open. For instance, an abstraction of the problem of designing a garage door would be to look for means of securing a garage in a way that protects a car from the weather and theft. [15]

The abstraction technique in the Pahl & Beitz methodology is based on careful analysis of the initial requirement list. Five steps are given, with which the essential design problem can be derived from the requirement list: [15]

1. Eliminate personal preferences.
2. Omit requirements that have no direct bearing on the function and the essential constraints.
3. Transform quantitative into qualitative data and reduce them to essential statements.
4. As far as it is purposeful, generalize the results of the previous step.
5. Formulate the problem in solution-neutral terms.

Following these steps, the essential function of the RockSense Imager Unit was defined as *"Attach the 3D imager to various conveyor belt support structures and enable its operation in varying operational environments."* A higher level of abstraction would certainly be possible for the RockSense system, but since the design process relates solely to the Imager Unit, the aforementioned problem statement is a good depiction of the crux of the design problem.

In order to visualize and better understand the functional decomposition of the product, a *functional diagram* that illustrates the functional structure was created. The functional structure is defined by dividing the overall function into subfunctions that produce the same outcome as the overall function when combined. The division process is continued for each subfunction until a sufficient level of simplicity is reached. Typically a functional diagram defines all relationships between different subfunctions through explicitly defined flows of material, energy, and signals. [15, 20] However, in the case of the Imager Unit, the material, energy, and signal flows were difficult to identify. For instance, the flow of thermal energy can alternate greatly depending on whether a cooling system, a heating system, or neither is being used. It was decided that a simplified functional diagram that simply lists the subfunctions of the product and illustrates their functional hierarchy would suffice. The Imager Unit's functional diagram is shown in Figure 15.

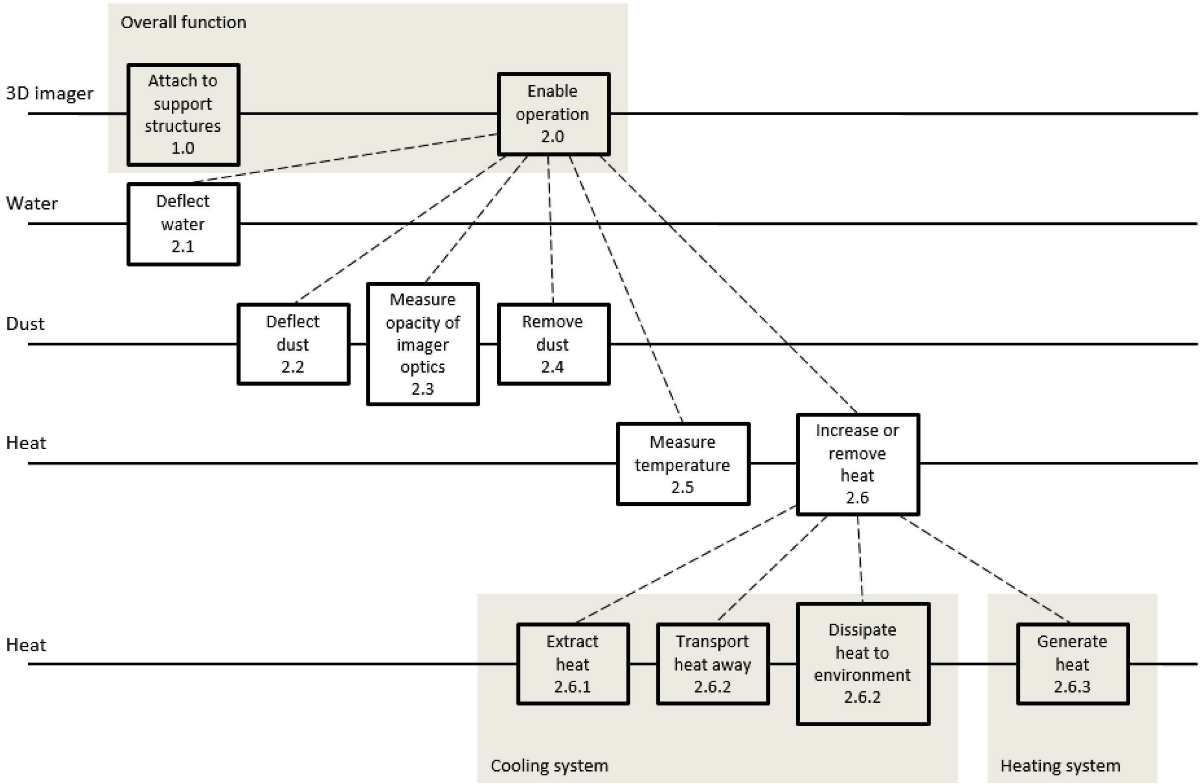


Figure 15: Functional diagram of the RockSense Imager Unit

5 Mechanical concept development

Based on the problem analysis and design parameters defined in the previous chapter, the process to produce a conceptual solution for the Imager Unit could be started. As mentioned in the previous chapter, a conceptual design that solves the overall design problem can be produced by finding a working solution principle for each of the subfunctions that make up the functional structure of the product.

The following subsections describe the process of finding and evaluating potential solution principles for each subfunction as defined in the functional diagram (Figure 15). The most suitable solution principle is selected for each subfunction. The overall conceptual design for the Imager Unit is the combination of the selected solution principles, as presented at the end of this chapter.

5.1 Search for solution principles

A large number of potential solution principles typically exist for any given subfunction. Finding the best possible solution principle requires thorough and comprehensive investigation to identify all conceivable alternatives. Changing a solution principle for a subfunction later on in the design process might require monumental changes to the design and cause a lot of additional work and expenses. Therefore it is crucial to map out all possible solution alternatives and systematically evaluate them to select the one that is most suitable for the given project [15]. A very extensive selection of tools and techniques for thoroughly exploring the space of solution alternatives has been described in engineering design literature. This thesis will not include a thorough examination of these methods, although the most essential techniques used during the RockSense project will be explained briefly.

The selection of techniques used to map out all possible solution alternatives for the RockSense Imager Unit subfunctions consist of a combination of *internal* and *external* search methods as defined by Ulrich & Eppinger [20]. Internal search methods utilize the expertise and creativity of the project team to generate novel solution concepts. Regular *brainstorming* sessions were used to generate a flood of ideas, from which the most potential ones could be chosen for further investigation and refinement. Brainstorming refers to a technique in which a group of people from various fields of expertise focus on a given problem and bring up any thoughts that come to mind. It is crucial to have an open minded and unprejudiced atmosphere where no ideas are disapproved, since even seemingly implausible ideas might trigger new ones [15].

External search methods aim to find existing solutions to the subfunctions that have not yet been discovered by the project team [20]. The most prevalent external method used for the RockSense project was researching different products and technologies related to a given subfunction. Patent and product searches were conducted in order to find any existing solutions that could solve the problem in question. Technical literature was reviewed in order to better understand the problem and possibly find new solutions not yet on the market. Additionally, experts outside the project team were consulted in order to gain new insights to the problem and discover new solutions.

The results of this long and arduous but essential process were compiled in to a *morphological matrix* as seen in Figure 16. The morphological matrix lists all the potential solutions that were considered for each subfunction with rough visual sketches that clarify the solution principles that are not self-explanatory.

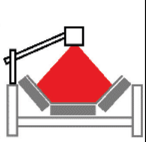
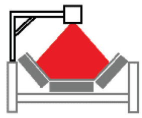
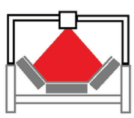
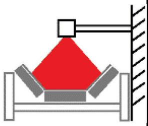
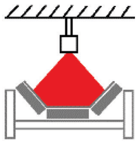
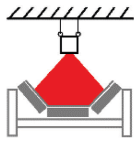
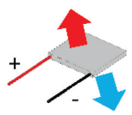
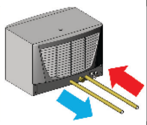
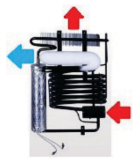
			Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
Attach to support structures 1.0			"Mic stand" 	"Gallow" 	"Arch" 	"Wall rod" 	"Roof rod" 	"Roof cable" 
Enable operation 2.0	**Deflect water 2.1**		Sealed enclosure					
	Deflect dust 2.2		Sealed enclosure					
	Measure opacity of imager optics 2.3		Laser intensity (software analysis)					
	Remove dust 2.4		Air jet	Manual cleaning				
	Measure temperature 2.5		PT100	Thermocouple	NTC			
	Increase or remove heat 2.6	**Extract heat 2.6.1**	Thermoeletric cooler 	Liquid chiller 	Compression cooler  [21]	Vortex tube (+compressor)  [22]	Absorption cooler  [23]	
		Transport heat away 2.6.2	Liquid circulation	Forced air circulation	Natural air circulation	Heat pipe	Conduction	
		Dissipate heat to environment 2.6.3	Natural convection	Forced air convection				
		Generate heat 2.6.4	Resistive heating element	Thermoeletric heater	3D imager's heating option			

Figure 16: Morphological matrix of the RockSense Imager Unit

After dividing the overall function into subfunctions and mapping out solution alternatives for each subfunction, an overall solution must be found by combining the subfunction solutions. According to the Pahl & Beitz methodology, this step involves analyzing the compatibility of the solution principles and coming up with complete concepts that include one or more solutions for each subsystem in a way that ensures a smooth and natural flow of energy, material, and signals throughout the system [15]. However, examination of the functional structure and morphological matrix for the RockSense Imager Unit revealed that a simpler approach could be possible in this particular case.

According to the RockSense business case, the product should include optional subfunctions that increase the product's operational environment and can be sold separately when they are required. It was decided that the heating and cooling systems as well as the dust removal from the Imager Unit optics would be offered as such optional modules. Because these subfunctions will only be added to the Imager Unit when needed, they must work independently of each other. Also, the basic functions need to work with or without any of the optional functions. Therefore, dependencies between the individual optional functions and the overall basic function cannot exist. Furthermore, upon examining the morphological matrix presented in Figure 16, it becomes apparent that only one of the subfunctions, "attach to support structure", has a significant effect on the mechanics of the overall basic function. The other subfunctions included in the overall basic function have only one or two mechanically similar solution alternatives. Therefore, the overall basic function can be solved simply by solving the subfunction "attach to support structure". Consequently, the basic functions as well as each optional function can be dealt with individually without concern for compatibility issues.

The following subsections describe the process of selecting the most suitable solution principles for each function. Finally, the resulting mechanical concept is presented.

5.2 Basic functions

To protect the Imager Unit electronics from dust and water, the equipment would have to be contained inside a sealed enclosure with an IP66 rating as defined in the engineering metrics. After a brief investigation of commercial options, it became obvious that the enclosure should be designed specifically for the Imager Unit. A commercial enclosure would require significant modifications, such as machining openings for the 3D imager's optics and the mechanical attachment interface, which would substantially increase the price and manufacturing time of a single enclosure. The mechanical design would also be restricted by the existing dimensions of the commercial enclosure. A proprietary enclosure on the other hand would allow complete freedom in the mechanical design and enable easy editing and versioning of the design. An enclosure made out of laser cut and bent sheet metal would also be very cost effective and quick to manufacture, as was revealed by a conversation with a local manufacturer.

Since the House of Quality analysis presented in Attachment 2 revealed "installations possible without modification" as the most important engineering metric, considerable time and effort was used in examining all the different solutions for the subfunction "attach to support structures". Numerous formal and informal meetings and discussions were held to determine which solution principle or a combination of solution principles would provide the most versatile attachment system. The main problem with selecting a solution principle was that according to prior experiences and interviews with operators in the industry, the supporting structures of conveyor belts are typically very specific to each site. To illustrate the problem, two very different conveyor belt assemblies are shown in Figure 17.

Figure 17: Conveyor belt structures in Mauritania (left) and Kevitsa, Finland (right)

Ultimately it was concluded that no single attachment system or combination of systems could be sufficiently versatile to enable attachment to any possible conveyor belt support structure. Some of the solution alternatives found for this subfunction could be used in some cases, but not in others. Furthermore, it was realized that operators in the MMMI typically have good abilities to modify and build simple support structures from e.g. welded steel bars. This information combined with the aforementioned conclusions lead to a decision to abandon the attempt to create a complete attachment system. Instead, a universal mechanical attachment interface would be designed to the Imager Unit that could be connected to from a wide variety of support structures built specifically for the installation site. The mechanical interface should enable the use of all of the attachment methods listed in the morphological matrix (Figure 16) as well as other methods that might be very specific to the site.

The process then began to find a conceptual solution for the mechanical attachment interface that would enable simple and easy attachment from all sides of the enclosure. After multiple brainstorming sessions, an idea of a flange connection system was discovered, the initial drafts of which are shown in Figure 18. The concept enables quick and easy bolt attachment and detachment that can be accomplished by a single person. The in situ support structure should include a plate with four threaded holes welded onto a solid pipe, which can then be attached to any suitable belt support structure. For further versatility, a lifting eye bolt was decided to be attached to all corners of the top of the enclosure. This allows the Imager unit to be attached using the “roof cable” attachment method included in the morphological matrix (Figure 16).This concept was determined suitable by the project team and accepted by the project management.

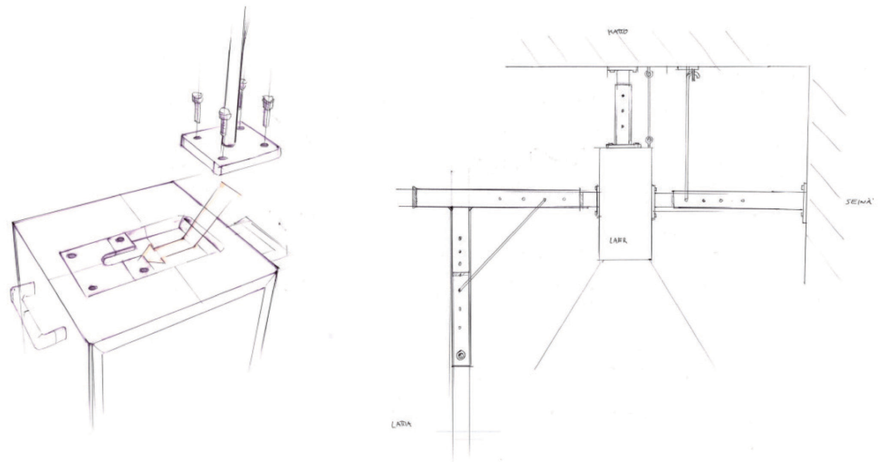


Figure 18: Initial drafts of the universal mechanical attachment interface of the Imager Unit

Two solution principles were considered for the temperature measurement function of the Imager Unit: Thermocouples and PT100-type thermometers. Both options are inexpensive, readily available, and being used in many other Outotec products. Thermocouples can measure a very wide range of temperatures, although this is often compromised by measuring accuracy. Thermocouples produce a temperature-dependent voltage which was considered susceptible to electrical interference in long cables compared to the temperature-dependant resistance of the PT100 or the NTC. The PT100 was seen as more suitable for the temperature range of the Imager Unit operational environment and its software implementation was considered easier than that of the NTC. For these reasons, PT100-type thermometers were selected to be used for monitoring the Imager Unit temperatures.

5.3 Cooling system

The seemingly simple problem of designing a working concept for the optional cooling system of the Imager Unit turned out to be one of the most problematic tasks in the RockSense project. The laws of thermodynamics state that two connected systems will naturally strive for thermal equilibrium, which means that a hot object placed in a cold environment will naturally cool itself and vice versa. A typical cooling problem in electronic systems is one where a subsystem or a single component is protected from overheating by enhancing the natural dissipation of thermal energy into the ambient environment. This type of problem can often be solved by a simple combination of heat sinks and fans that increase the rate of heat flow from the component to the environment.

The 3D imager in the RockSense Imager Unit, however, has to be kept in a temperature lower than the ambient temperature. This is more problematic than the general case described above, since the cooling system has to act against the natural flow of thermal energy rather than enhancing it. Furthermore, the extremely dusty operational environment makes the use of fans problematic. Firstly, a fan mounted on the Imager Unit would likely mobilize the airborne particles around the Imager unit and cause the imager optics to be covered in dust much faster than normal. Secondly, some of the tiny rock dust particles would likely make their way inside a fan's bearings and significantly shorten its lifespan and maintenance interval. The Imager Unit's placement above the conveyor belt means that heavy heat sinks or other large cooling equipment cannot be attached to it. Additionally, the cooling system cannot compromise the enclosure's compactness, which can be problematic if a medium such as air or water is used to transport thermal energy away from the enclosure.

5.3.1 Thermodynamic calculations

The engineering metrics state that the maximum operational environment temperature should be at least 55°C, whereas the 3D imager can only operate in temperatures up to 45°C. In order to leave some margin for error and to ensure functionality of the 3D imager, it was decided that it should be kept in a temperature of 40°C or less in all ambient temperatures within the operational environment. In order to determine the required cooling power, the rate of heat flow from the ambient environment into the enclosure had to be calculated in a situation where the internal temperature of the enclosure is 40°C and the ambient temperature 55°C.

The most complex part of the calculation of heat flow through the enclosure walls relates to the boundary layers between the enclosure surface and the air inside and outside the enclosure. Thermal transport in surface-gas boundaries is a complex phenomenon that consists of all three heat transfer mechanisms: conduction, convection and radiation. Typically, gases such as air have low thermal conductivities and thus, conduction at such surface boundaries has little significance. Therefore, convective and radiative heat transfer must be determined in order to obtain realistic values for the heat flow through the boundary layers.

The convective heat transfer is heavily dependent on the state of the gaseous environment. For instance, motion initiated by wind would increase the thermal transport at the surface significantly. Since the wind conditions around the Imager Unit are unknown, a worst case scenario is assumed where the thermal resistance between the external air and the enclosure surface is nonexistent. The same assumption was made for the internal surfaces, since it was not yet known whether forced air flow would be used to assist the cooling process. The maximum heat flow through the enclosure walls could then be calculated simply based on the thermal resistance of the wall material.

The enclosure dimensions were estimated based on the size of the imager unit and an estimation of spatial requirements of other equipment inside the enclosure. Thermal insulation can significantly decrease the unwanted heat flow through the enclosure walls, so a 10mm thick polyurethane foam layer was decided to be added on the inner enclosure walls with the cooling system. The material properties used to calculate the heat flow are shown in Table 4.

Table 4: Estimated thermodynamic boundary conditions of the Imager Unit

Boundary condition	**Value**
Enclosure dimensions (L x H x D)	540 x 235 x 220 mm
Enclosure material	Stainless steel
Enclosure thickness s_{St}	1,5 mm
Enclosure thermal conductivity λ_{St}	17 W/(m*K) [24]
Insulation material	Polyurethane foam
Insulation thickness s_{PolU}	10 mm
Insulation thermal conductivity λ_{PolU}	0,026 W/(m*K) [24]
Heat generated by 3D imager	7 W

The heat flow q through the enclosure and insulation is calculated as follows: [25]

$$q = A \cdot \frac{\Delta T}{\frac{s_{St}}{\lambda_{St}} + \frac{s_{PolU}}{\lambda_{PolU}}} = 0{,}595 m^2 \cdot \frac{15\text{K}}{\frac{0{,}0015m}{17\frac{W}{mK}} + \frac{0{,}01m}{0{,}026\frac{W}{mK}}} = 23{,}19W \quad (1)$$

When the 7W heating power generated by the 3D imager was taken into account, a cooling power requirement of 30,19W was obtained.

5.3.2 Solution alternatives

As shown in the Imager Unit functional diagram (Figure 15) and the morphological matrix (Figure 16), the cooling system function was divided into three subfunctions, each of which has several potential solution principles. As mentioned in section 4.3, the solution principles should then be combined to create variants for the overall solution. The variants that contradict the engineering metrics or customer needs were omitted from further review, as well as ones that do not enable smooth flow of materials, signals, and energy. The solution variants derived from the morphological matrix and selected for further analysis are presented in Figure 19.

	Remove heat (from 3D imager)	Transfer heat (out from enclosure)	Dissipate heat (into environment)
Solution 1	Peltier element	Liquid circulation	Natural convection / Forced air convection
Solution 2	Peltier element	Heat pipe	Forced air convection
Solution 3	Peltier element	Conduction	Natural convection
Solution 4	Liquid chiller	Liquid circulation	Forced air convection
Solution 5	Compression cooler	Vapor	Natural convection
Solution 6	Compression cooler	Forced air circulation	Natural convection
Solution 7	Vortex tube (+ compressor)	(Vortex tube)	(Vortex tube)
Solution 8	Absorption cooler	Forced air circulation	(Absorption cooler)

Figure 19: Solution variants for the cooling system

A systematic method for selecting the most suitable cooling concept, as suggested by Pahlz and Beitz [15] as well as Ulrich and Eppinger [20], was used. This method includes creating a list of weighted selection criteria that accurately describes the features and attributes that the cooling system should include. The concepts are then evaluated and scored based on each individual criterion and an overall score for each concept is produced. If the analysis is carried out correctly, the resulting scores should provide a direct numeric indicator of the suitability of each cooling concept. The list of criteria for the cooling system, composed by the RockSense project team, is as follows:

1. Low costs
2. Low maintenance requirements
3. Small and lightweight (in Imager Unit)
4. Easy installability and maintenance
5. Minimal disturbance to other functions
6. Robust against dust, vibration etc.
7. Min. storage temperature (below -30°C)
8. Max. operating temperature (above 55°C)
9. Large cooling power range
10. Energy efficiency
11. Expected lifespan
12. Adjustable cooling power

13. Overall compactness
14. Applicability to other Outotec products
15. Simplicity (mechanical, electrical, etc.)

The relative importance for each criterion was determined by a *pairwise comparison matrix*. Each criterion is compared to all the other criteria and given one "point" if it is considered more important than the criterion it is being compared to. A weight coefficient is then calculated for each criterion by dividing its overall score by the sum of all scores from every criterion. The pairwise comparison matrix can be seen in Attachment 3.

The concept alternatives were then compiled into a *concept evaluation matrix*, in which each concept is given a score based on how well the given concept is considered to fulfill each criterion. The concepts were scored in the range from 1 to 10, with 1 representing a very unsuitable solution and 10 an ideal solution. Each score was then multiplied by the weight coefficient for the given criterion, derived from the pairwise comparison matrix. The final score for each concept is calculated as the sum of all weighted scores for the given concept. The finished concept evaluation matrix is shown in Attachment 4.

Based on this concept evaluation method, the highest ranking solution based on a thermoelectric cooler (TEC), thermal conduction, and a passive heat sink was selected for further investigation.

5.3.3 Solution 1: TEC + conduction + passive heat sink

This cooling concept is based on a *thermoelectric cooler* combined with a passive heat sink. A TEC is a semiconductor component that acts as a heat pump when current is run through it, i.e. one face of the flat element turns hot and the other one cold. The TEC is placed in an opening in the enclosure wall with the cold face inside the enclosure. Finned aluminum radiators with large surface areas are attached to both sides of the TEC in order to increase the heat transfer from inside the enclosure to the external environment. The concept sketch is illustrated in Figure 21.

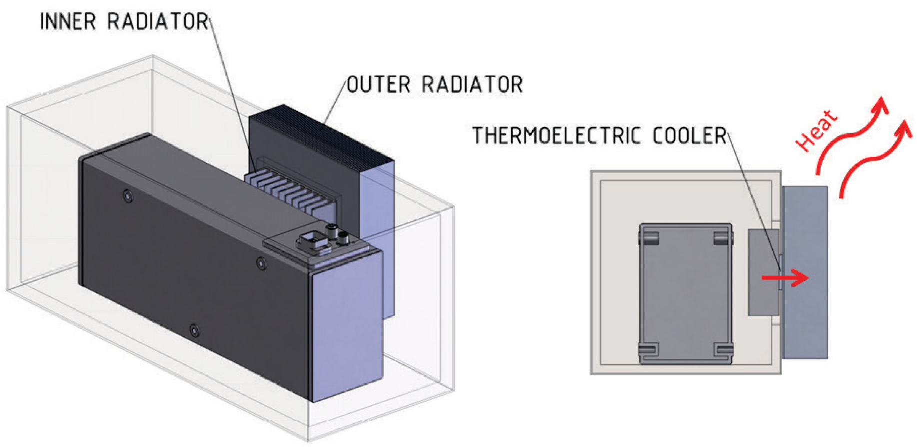


Figure 20: Sketch of the cooling concept based on a TEC and natural convection

This cooling concept would provide reliable and robust cooling with no moving parts and very minor maintenance requirements. However, there was skepticism within the project team about whether or not the natural convection with no fans would provide sufficient heat flow from the outer radiator to the ambient environment. Furthermore, if the outer radiator was covered in dust, its thermal resistance would be substantially lowered, further hindering the natural convection. It became clear that a practical test would be necessary in order to validate the cooling concept.

The main disadvantage of the TEC technology is the generally poor thermal efficiency of the TEC elements. As the TEC moves thermal energy from one face to the other, it also generates waste heat that needs to be transported away from the hot face. The amount of waste heat generated varies greatly with the heat load being pumped, temperature difference between the faces, temperature of the hot face, and the model of the TEC. The coefficient of performance (COP) typically varies between 10 and 50 percent. Therefore, the TEC model and the operating current would have to be selected carefully in order to optimize the cooling system's efficiency.

The temperature difference between a TEC's hot and cold face is typically constant with a given input current and hot face temperature. Therefore, to keep the cold face at a constant temperature, the temperature of the hot face would also need to remain constant. For safety reasons, it was decided that the heat sink surface temperature should not exceed 80°C. This decision was also backed by the fact that most TEC models report a maximum hot face temperature of 80…90°C. The parameters defined for the hot and cold faces of the TEC and the required heat load moved through it could then be used to select a suitable TEC model. The datasheets of the most promising TEC models from four major manufacturers were investigated and the results compiled into a selection chart as seen in Attachment 4. By combining two suitable TECs and using a specific operating current, a thermal efficiency of 60% could be reached, which is substantially better than the performance of a typical TEC.

After the TECs had been selected and acquired, a mockup prototype of the enclosure was built out of plywood according to the estimated enclosure dimensions shown in table 4. Styrofoam plates were glued to the inner surfaces of the box to simulate the polyurethane insulation. A finned aluminum heat sink, considered as large as could possibly be installed on the Imager Unit, was used as the outer radiator. Smaller aluminum radiators were placed on the cold faces of the TECs inside the enclosure.

The mockup enclosure with the cooling system attached was taken to a sauna with an electric stove so that the ambient temperature could be maintained near 55°C. The 3D imager was placed inside the enclosure and turned on, so that the heat generated by the imager would be taken into account. The test setup is shown in Figure 22.

Figure 21: TEC + conduction + passive heat sink cooling concept test setup

Six thermometers were used to monitor the imager's surface temperature, the TECs' face temperatures, and the ambient temperature. It was decided that the test would begin at room temperature, after which the ambient temperature would be raised and maintained at 55°C. The test would continue until a thermal equilibrium is reached or the imager temperature rises to 45°C. The test results can be seen in Figure 23.

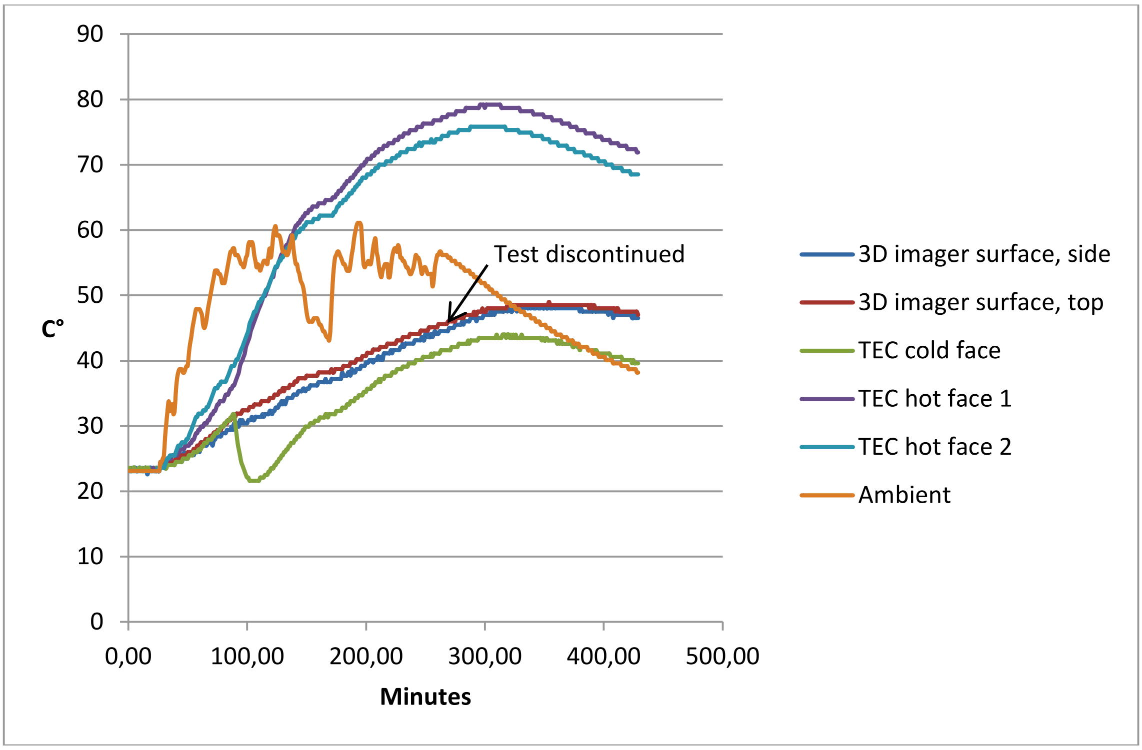


Figure 22: TEC and natural convection cooling concept test results

The test results clearly indicate that the cooling concept is not able to keep the 3D imager temperature within its operational range in an ambient temperature of 55°C. The TECs worked as intended, keeping a constant temperature difference between their hot and cold faces. However, the outer radiator was clearly not capable of dissipating the heat created by the TECs efficiently enough to keep the hot side temperature at an acceptable level by mere natural convection. Additional experiments using fans, various operating currents, and even water spray were conducted with the test setup but a suitable solution to make this cooling concept work was not discovered. Thus, a decision was made to abandon this cooling concept and move on to the concept ranked second in the evaluation matrix (Figure 20).

5.3.4 Solution 2: TEC + heat pipe + forced air convection

The second choice for the Imager Unit's cooling concept is also based on a TEC. In this concept, a *heat pipe* is used to transport the unwanted thermal energy further away from the Imager Unit, where a fan could be utilized to dissipate the heat into the environment. A heat pipe is a closed pipe system containing a liquid with a relatively low boiling point. The liquid is vaporized by the heat flow from the TEC's hot face, which transforms into the vapor's latent heat. The vapor travels along the pipe system to another location, where it condenses back into a liquid, releasing the latent heat. The thermal energy released from the vapor can then be absorbed by a heat sink and dissipated into the environment by forced air convection with the help of a fan. Gravity then pulls the liquid back to the hot side and the cycle repeats. The radiator and fan could be placed inside a filtered enclosure that enables airflow across the heat sink surface but prevents dust from covering it or entering the fan bearings. Like the first cooling concept, this one should enable reliable cooling with low maintenance requirements. The concept is illustrated in Figure 24.

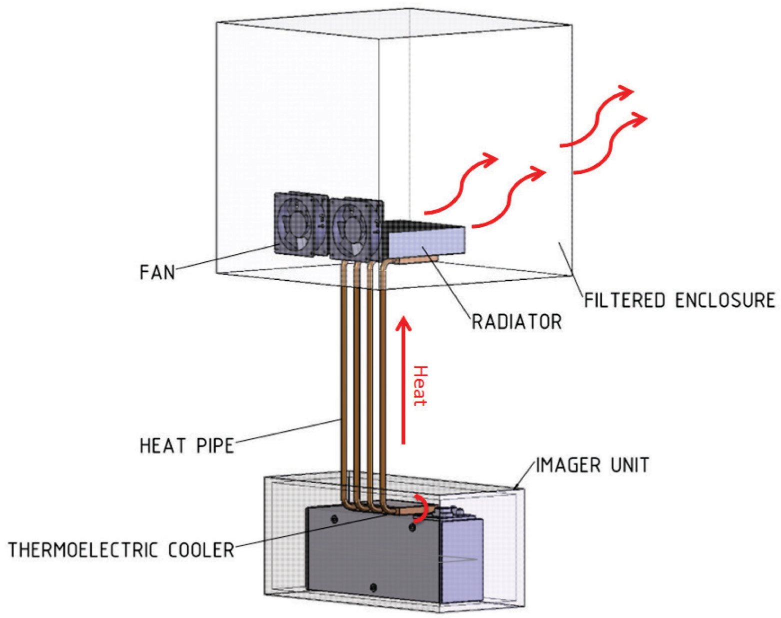


Figure 23: Sketch of the cooling concept based on a TEC and heat pipe

However, there are some disadvantages related to heat pipes. Firstly, in order for the cooling system to work, the filtered enclosure containing the fan and radiator needs to be placed above the Imager Unit, which may not be possible in some installation sites. Secondly, a thorough investigation into commercial heat pipe technologies was done and a product that could provide sufficient flexibility and distance between the Imager Unit and the filtered enclosure was not found. It was further concluded that designing an entirely novel heat pipe system would be far beyond the expertise of the project team and would not be possible with the available resources. Therefore, the heat pipe concept was also abandoned and the third option from the evaluation matrix (Figure 20) was taken under inspection.

5.3.5 Solution 3: Absorption cooler + forced air circulation

The third cooling concept uses an *absorption cooler*, based on a combination of water, ammonium, and hydrogen gas in a closed pipe system that enables using heat as the power source for the cooling process. To summarize the absorption cooling process, an electrical heater or a gas burner is used to heat an ammonium solution to its boiling point. The vaporized ammonium rises to the top of the pipe system where it is condensed to liquid ammonium and brought into contact with hydrogen gas. The hydrogen gas induces a radical drop of pressure in the liquid ammonium, which causes it to evaporate and absorb heat from its environment. The piping system is designed so that the system is brought back to its initial state by gravity and the cooling cycle can repeat as long as heat is provided to boil the ammonium solution. An absorption cooler does not include any moving parts and has very low maintenance requirements, making it a very suitable candidate for the Imager Unit’s cooling system. An additional advantage is that it does not require heat sinks or fans to dissipate unwanted thermal energy to the environment. A commercial absorption cooler can be seen in Figure 25.

Figure 24: A commercial absorption cooler [23]

Because absorption coolers are fairly large and heavy, attaching one directly to the Imager Unit would be problematic. This cooling concept solves the problem by installing the absorption cooler in a separate enclosure away from the belt, and creating a closed air circulation system between the Imager Unit and the absorption cooler's cold part to transport cold air to the 3D imager. The concept is illustrated in Figure 26.

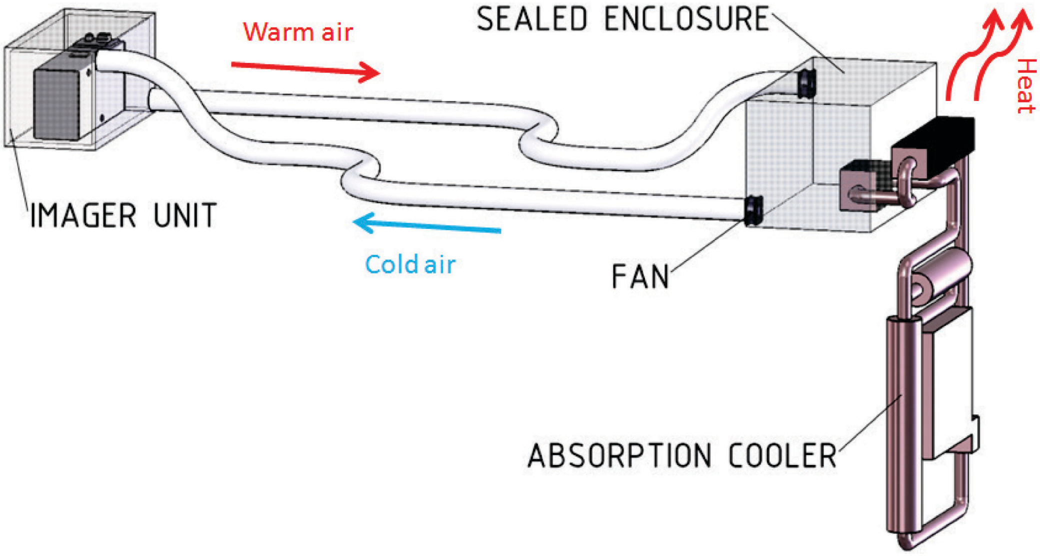


Figure 25: Sketch of the cooling concept based on an absorption cooler and forced air circulation

In order to verify the viability of this cooling concept, an investigation on commercial solutions for absorption coolers was conducted. Unfortunately, a supplier that could meet the requirements for price, quantity, and delivery time could not be found. The absorption cooler units are generally sold in bulk to manufacturers of refrigerators and not in quantities small enough to meet the RockSense project demands. Therefore, like the previous cooling concepts, this too had to be abandoned and the next cooling concept on the analysis matrix (Figure 20) taken under analysis.

5.3.6 Solution 4: TEC + liquid circulation + forced air convection

The fourth cooling concept is again based on a TEC and uses water as the medium for heat transfer. A water block is attached on the hot face of the TEC and a radiator placed in a filtered enclosure away from the Imager Unit, through which the excess heat can be dissipated into the environment by forced air convection. A pump is used to circulate water between the radiator and the TEC. The TEC's cold face could be attached directly on the 3D imager's aluminum body in order to maximize the heat flow from the 3D imager to the water block. The concept is illustrated in Figure 27.

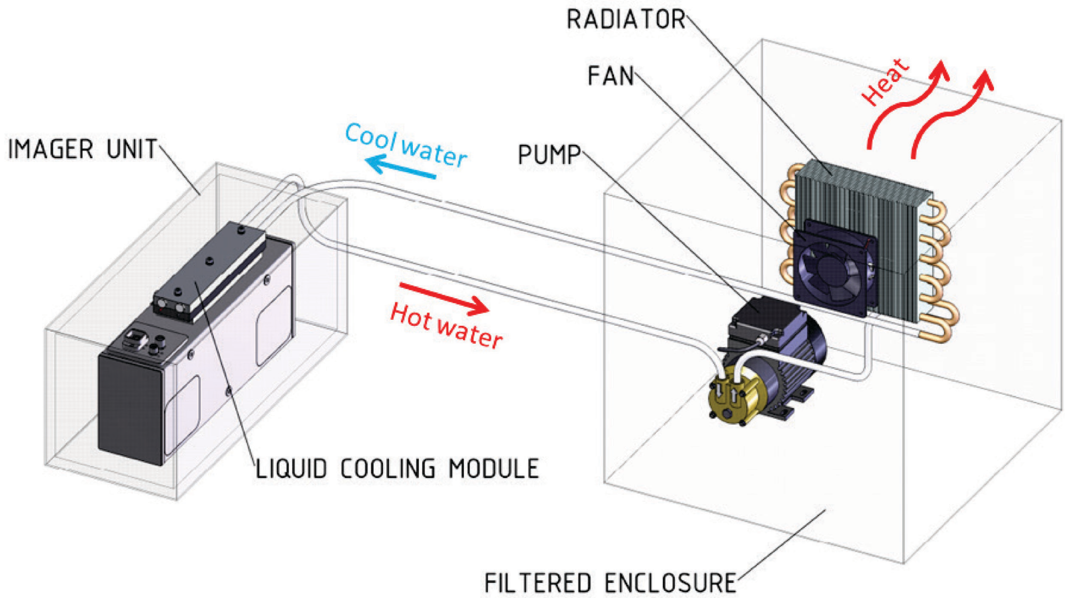


Figure 26: Sketch of the cooling system based on a TEC and liquid cooling

Even though the pump and the radiator fans add moving parts to the cooling concept, their robustness and maintenance requirements were considered sufficient if placed inside a filtered enclosure. Furthermore, because similar systems are used in other Outotec products, components for the cooling system are readily available. In order to validate the concept, another practical test was required. A water cooling module containing the TECs and the water block was chosen based on its availability within the company and sufficient cooling power. A similar test setup as with the first cooling concept was built and the test was conducted with the same procedures. The test results can be seen in figure 28.

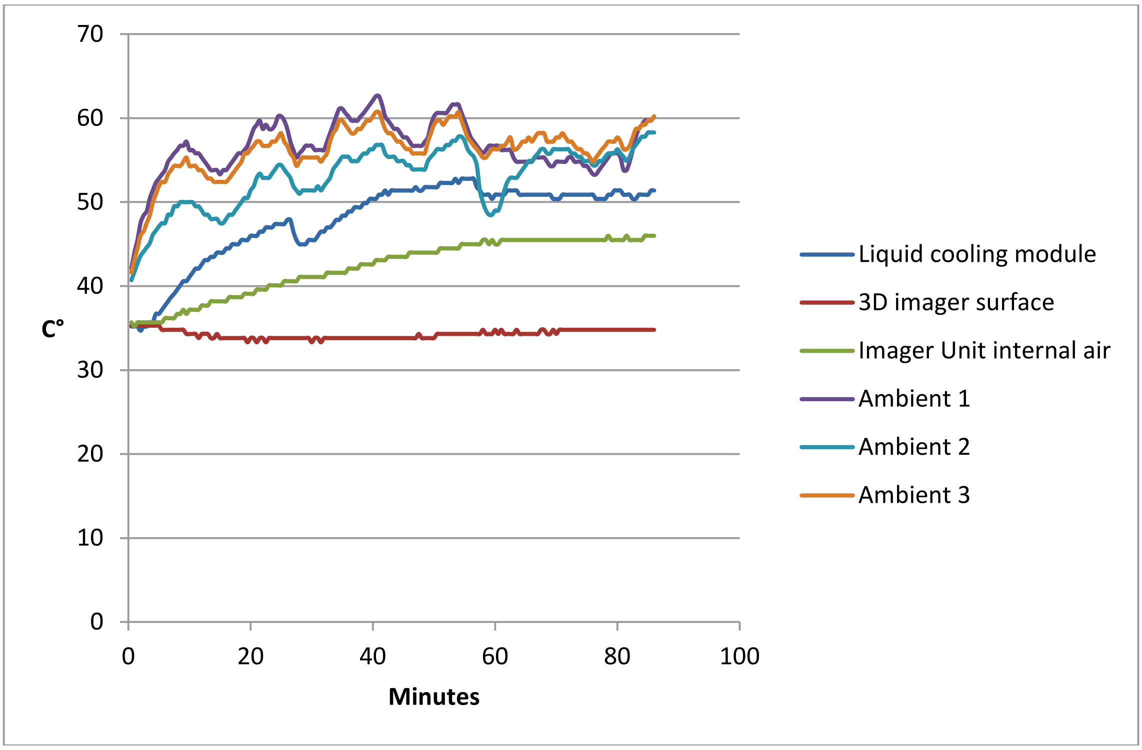


Figure 27: TEC and liquid cooling concept test results

The test results show that the system reached thermal equilibrium with acceptable temperature levels and it was concluded that this cooling concept is capable of maintaining the 3D imager temperature below 40°C in an ambient temperature of 55°C. Based on this result, the cooling concept based on a TEC and a closed water circuit could be validated and selected to be used as the optional cooling solution for the RockSense Imager Unit.

5.4 Heating system

Three solution principles were considered for the subfunction "generate heat", as seen in the morphological matrix (Figure 16).

5.4.1 Solution selection

The 3D imager selected for the RockSense project includes a heating option that could be added to the imager for an additional cost. This heating method would naturally be the easiest to implement, but after some discussion within the project team it was concluded that the imager's heating option would be too expensive for the project budget. Another solution would be to reverse the operating current on the cooling system's TEC so that the TEC's hot face was against the imager body. However, since the cooling and heating systems need to be able to function independently of each other, this method was not considered acceptable.

The final solution principle was to use a simple resistive heating element that converts electric current directly into thermal energy. This solution enables a very simple and robust heating system with only component, no moving parts, and practically nonexistent maintenance requirements. Thus, a resistive heating element was selected to be used for the Imager Unit's optional heating system.

5.4.2 Thermodynamic calculations

In order to select a suitable heating element for the Imager Unit, the required heating power was to be calculated. The calculations were conducted based on the thermodynamic boundary conditions presented in Table 4 in subsection 5.3.1, and using 5°C as the internal temperature and -30°C as the external temperature. As with the cooling system, the air flow conditions inside and outside the enclosure are unknown and therefore the thermal resistances of the surface-gas boundary layers are assumed as nonexistent. The heat flow through the enclosure can be calculated according to (1):

$$q = A \cdot \frac{\Delta T}{\frac{s_{St}}{\lambda_{St}} + \frac{s_{PolU}}{\lambda_{PolU}}} = 0{,}595m^2 \cdot \frac{35\mathrm{K}}{\frac{0{,}0015m}{17\frac{W}{mK}} + \frac{0{,}01m}{0{,}026\frac{W}{mK}}} = 54{,}11W \tag{2}$$

Considering the 7W of heat generated by the 3D imager, a minimum heating power of 47,11W was obtained.

5.5 Dust removal system

Two solution options, air cleaning and manual cleaning, were considered for the subfunction “remove dust”. The dust removal would be focused on the 3D imager’s optics, since the rest of the equipment would be protected by the Imager Unit enclosure. The solution based on an air jet system would include directing a stream of high velocity air towards the imager optics, which would remove any dust particles attached to it. This solution would involve an air compressor near the Imager Unit, a suitable nozzle system attached to the Imager Unit, and all the piping required to transport the pressurized air. The other solution alternative would be to simply clean the optics manually as part of the routine maintenance of the Imager Unit. Clearly the latter solution principle would be significantly easier to implement, although there was doubt of its feasibility within the project team. According to the engineering metrics, the maintenance interval of the Imager Unit should be at least 6 months. It was not known whether or not the optics would remain sufficiently opaque for a 6 month period in dusty conditions without an additional dust removal system.

In order to gain more understanding on the dusting problem, the test installations at the Kevitsa mine were looked into. The test installations had run successfully for close to six months without any kind of dust removal system. It was decided that the imager lenses at Kevitsa would be cleaned manually and the laser intensity trends compared before and after the cleaning. Thus, the relationship between the optics dusting and imager performance could be better understood. Figure 29 shows the laser intensity trend before, during, and after the cleaning of the imager optics on one of the Kevitsa test installations.

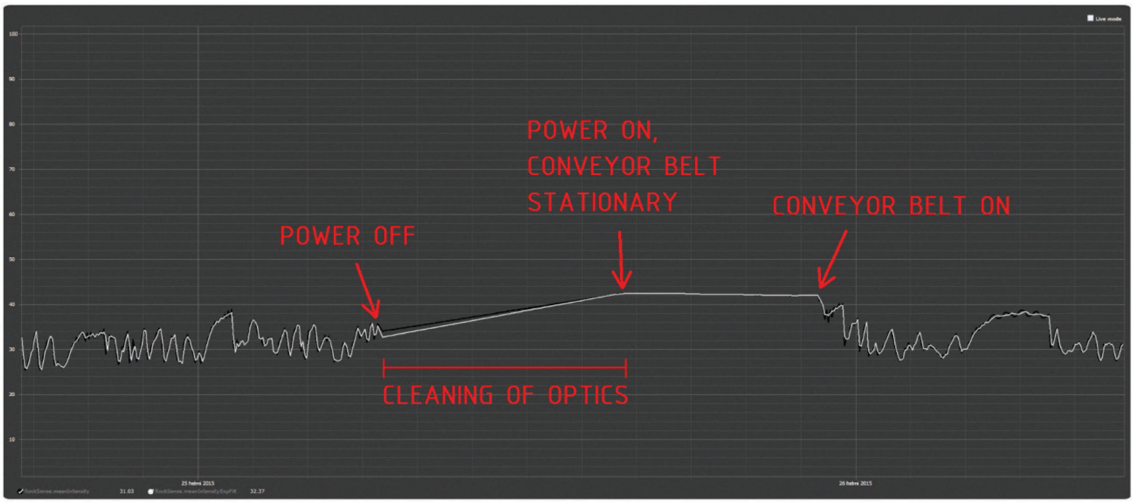


Figure 28: Laser intensity trend of a Kevitsa test installation before, during, and after cleaning of the imager optics

The intensity graph showed little to no change on the imager performance as a result of cleaning the imager optics. This observation led to a conclusion that manual cleaning is a working solution for the dust removal subfunction. However, it was concluded that the imager performance in future installations should be carefully monitored and the possibility to design an additional dust removal system later in the product's life cycle should be considered during the mechanical design phase.

5.6 Overall solution

The final concept for the RockSense Imager Unit combines all the solution principles that were selected as described in the previous subsections. A sketch of the overall concept including all the optional subfunctions is presented in Figure 30.

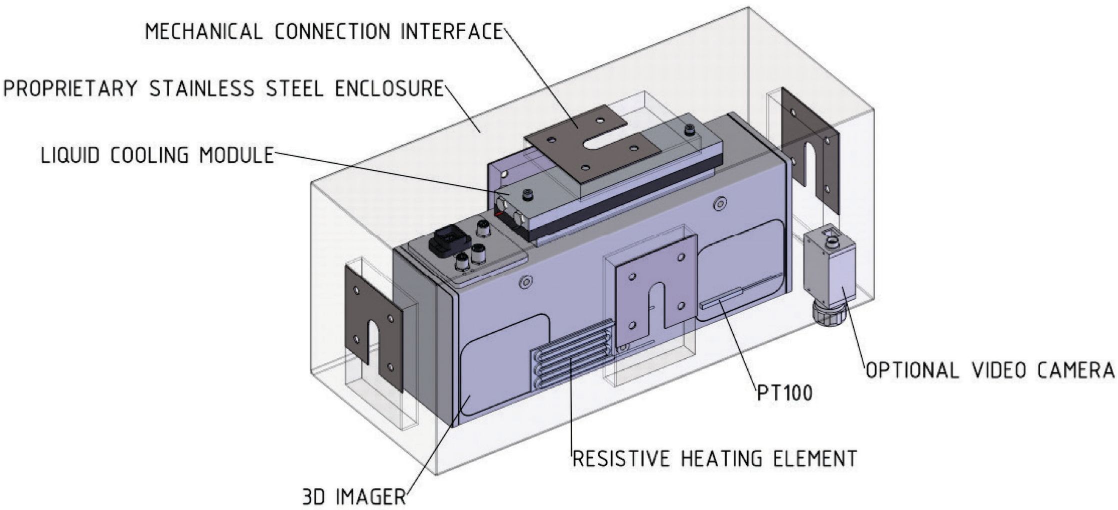


Figure 29: Sketch of the overall Imager Unit concept

6 Embodiment design

Having created a conceptual solution for the RockSense Imager Unit as described in the previous chapter, the design process could be taken from the abstract to the concrete. A detailed embodiment design was to be made, the goal of which is to precisely and explicitly specify the physical structure of the product. Each individual part has to be designed with all the details necessary for manufacturing and assembly. Based on the embodiment design, the parts are then manufactured or purchased from suppliers, and the prototype is assembled. The following subsections go through the various phases of the embodiment design process, after which the assembly of the Imager Unit prototype is described.

6.1 Mechanical design

Creating a mechanical design from which the physical prototype can be derived requires careful consideration of numerous design aspects. The function, production, assembly, costs, durability, compatibility, and operation of each individual component as well as the overall arrangement needs to be considered. Furthermore, the manufacturing process for each proprietary component requires careful consideration, since the manufacturing cost for an individual component can vary remarkably according to materials, shapes, sizes, and manufacturing tolerances.

All of the aforementioned design aspects need to be considered in all phases of the mechanical design process. All components and subsystems within an assembly are interrelated, which means that adding or changing one part usually leads to changes in other parts as well. Consequently, the mechanical design process of a complex system is generally highly iterative as opposed to strictly linear. This also holds true for the RockSense Imager Unit design. However, to minimize the workload related to redesigning parts and subsystems, the design process was started with the subsystems that have the most crucial bearing on the embodiment design. These were identified as the enclosure and imager attachment systems and the universal connection interface. After these subsystems, the cooling, heating, and video camera options were designed, followed by laser safety systems.

3D computer aided design (CAD) modeling was used as the primary design method in the Imager Unit design process. An iterative design process often requires components and arrangements to be edited, which can be easily done in the CAD model. The 3D model also enables simulations and structural analyses to be conducted easily and illustrates the design in a way that can reveal potential design errors before resources are spent on prototyping. Furthermore, a majority of the product documentation, such as manufacturing documents and assembly instructions, can be easily derived from the CAD-model. Commercial components were also modeled as accurately as possible based on information from datasheets and other product documentation. This allows the spatial requirements and attachment mechanisms of the commercial components to be factored in easily and intuitively.

The following subsections describe the mechanical design process and the most essential decisions behind the design. For the sake of clarity, the process will be described here in a sequential fashion, even though as previously mentioned, the process was highly iterative and involved repeated edits to previously designed components according to new design decisions.

6.1.1 Basic structure

The mechanical design process was started with the enclosure, since it defines the external dimensions of the assembly as well as the spatial constraints for the equipment. As mentioned in subsection 5.2, the enclosure would be made of laser cut and bent sheet metal. There was some discussion on whether the enclosure should be made out of aluminum or stainless steel, which eventually led to a decision on stainless steel. Although an aluminum enclosure would likely be lighter than a steel enclosure, it was unclear how the material would react in the harsh environment of a mineral processing plant over a long time period. Many Outotec products that operate in similar conditions use stainless steel components and the material is known to perform well in the harsh environment. Furthermore, the elasticity and thermal conductivity of aluminum would be unfavorable for the cooling system and mechanical attachment interface of the Imager Unit. The sheet metal thickness was chosen as 1,5mm based on an evaluation of the required material stiffness.

Since the mechanical connection interface concept described in subsection 5.2 can be installed on any side of the enclosure except the bottom, it was determined that the enclosure should have a detachable bottom, through which the equipment can be installed and accessed. Thus, all the attachment points would be on a single solid frame, allowing a direct translation of force throughout the enclosure.

Since the direction of imaging is downwards, the 3D imager would be installed on top of the detachable bottom of the enclosure. Transparent windows between the imager and the material being measured were seen as unfavorable, since they would reduce the laser's intensity. Therefore, the enclosure bottom would require openings for the imager optics. In order to keep the enclosure sealed from dust and water, a rubber gasket is required between the imager and the enclosure bottom. To ensure an effective seal, the 3D imager should be compressed against the enclosure bottom with the sealing component in between.

Rather than attaching the 3D imager directly to the enclosure bottom, a solution emerged that would offer a more direct translation of force from the Imager Unit's attachment points to its center of mass. The solution involves two plastic components attached to the enclosure frame with machined slots designed to fit the 3D imager ends. In order to secure the 3D imager in place, another plastic component was designed under the imager, attached to the enclosure bottom, with a machined inset that prevents the imager from moving in the lateral plane. The 3D imager would be compressed between the plastic components, holding the 3D imager securely in place as well as ensuring an effective seal under the imager. The solution is illustrated in Figure 31.

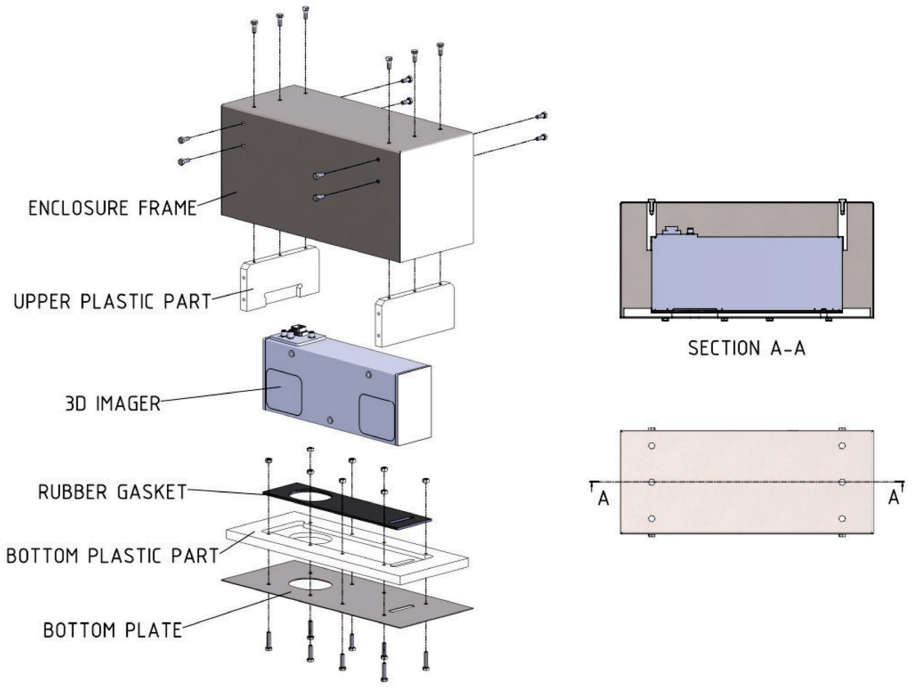


Figure 30: Imager attachment system

The plastic parts would be made out of PVC, since it provides sufficient mechanical properties for force translation, is cheap, and is very easy to work on with machining equipment. The parts were designed to be machined by a CNC mill, and the tool path had to be considered in order to avoid creating a shape that is impossible to create with a CNC mill. The thickness of the PVC parts was selected as 20 mm, since raw PVC plates with this thickness would likely be readily available to most manufacturers. Not having to modify the parts' thickness in the manufacturing phase decreases machining time and manufacturing costs. The initial design of the plastic components can be seen in Figure 32.

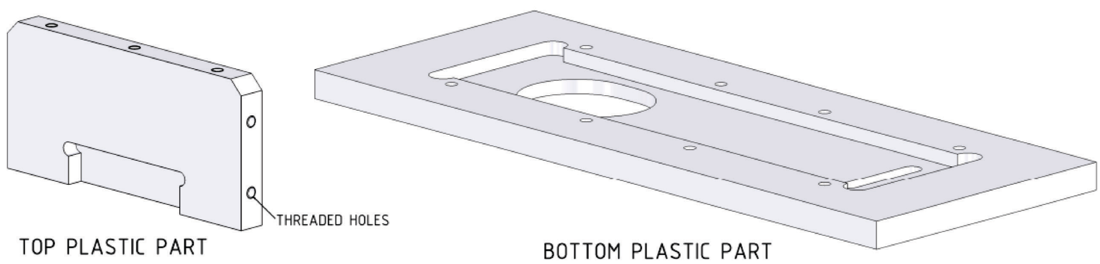


Figure 31: Plastic parts of the Imager Unit enclosure

The attachment of the enclosure bottom to the enclosure frame was to be designed in a way that allows its position to be adjusted vertically. Vertical adjustment enables compressing the imager unit between the frame and the bottom. Furthermore, the bottom should be easily removed and reattached during maintenance. After some brainstorming, a simple solution was found that involves a block with a threaded hole to be attached to all inner corners of the enclosure frame. Stainless steel bolts would be used to attach the enclosure bottom to these threaded holes through openings in each corner of the bottom. In order to seal the edges of the enclosure bottom, a D-shaped rubber sealing would be attached to the edge flanges of the bottom plate, as illustrated in Figure 33. The dimensions of the bottom plate and the frame would be designed so that inserting the bottom plate produces a tight seal around the enclosure frame.

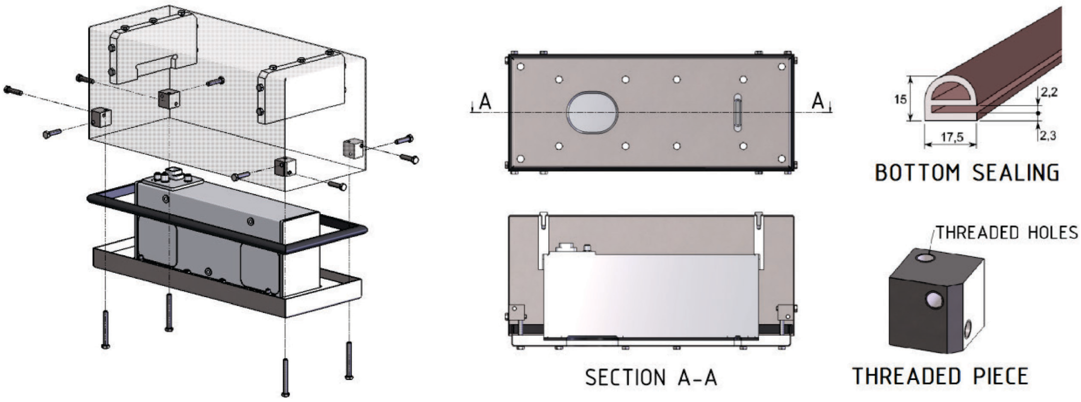


Figure 32: Bottom sealing mechanism

6.1.2 Universal connection Interface

The mechanical connection interface concept described in subsection 5.2 includes an attachment option from each side of the enclosure. Rather than having a fixed attachment point on every enclosure face, a removable attachment flange was designed from 3 mm thick stainless steel sheet metal as illustrated in Figure 34 Each face of the enclosure would have fixed holes where the flange could be connected to. This system should provide sufficient flexibility to accommodate many different installation sites. Additionally, holes on the top corners of the enclosure were added. Lifting eye bolts could be attached to these holes to enable cable attachments, as seen in Figure 34.

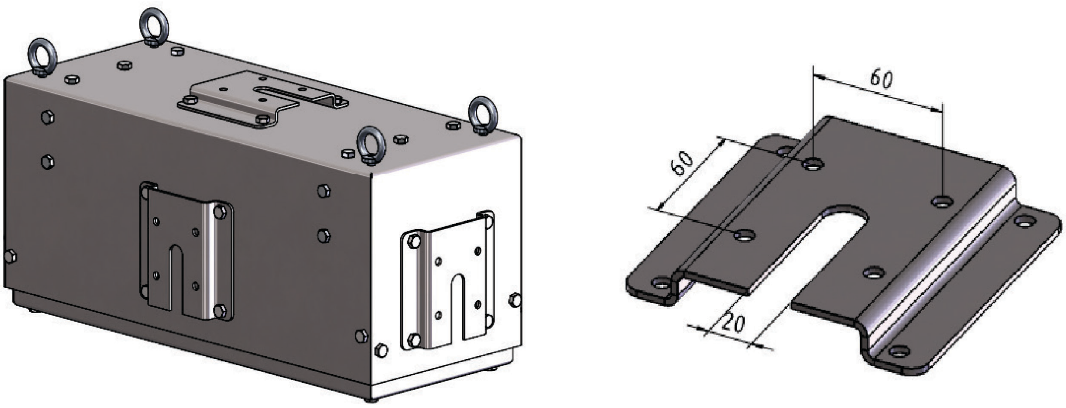


Figure 33: Mechanical connection flanges

Power and signal cables would be taken from the Control Cabin to inside the Imager Unit using a single 32-pin cable. Sites where the conveyor speed is not constant require a rotary encoder to be connected to the 3D imager for belt speed measurement. Additionally, separate Ethernet cables are used to transfer the 3D imaging data and the optional video feed from the Imager Unit to the Control Cabin. Since the cable distance between the Control Cabin and the Imager Unit can be up to 20 meters, and the Imager Unit has to remain sealed, the cables could not be plugged directly in to the equipment inside the Imager Unit. Instead, sealed connectors would be mounted on the enclosure frame, through which the connections can be made inside the Imager Unit. Designing the mechanical connector flange system gave rise to an idea to use the same approach for the electrical connector interface of the Imager Unit. A separate flange could be designed to house all the necessary connectors, which could then be attached to any side of the enclosure depending on the installation site, as seen in Figure 35. Furthermore, yet another connector flange could be designed for the pipe connectors required by the optional cooling system. To make room for the cables and pipes inside the enclosure, an opening was added in the middle of the bolt connection holes on each side of the enclosure frame. In order to seal the openings, rubber gaskets were designed that could be placed between the connector flanges and the enclosure frame. A dummy flange with the purpose of sealing the enclosure openings when a connector flange is not attached was also designed. Figure 35 illustrates the universal connection interface on the Imager Unit.

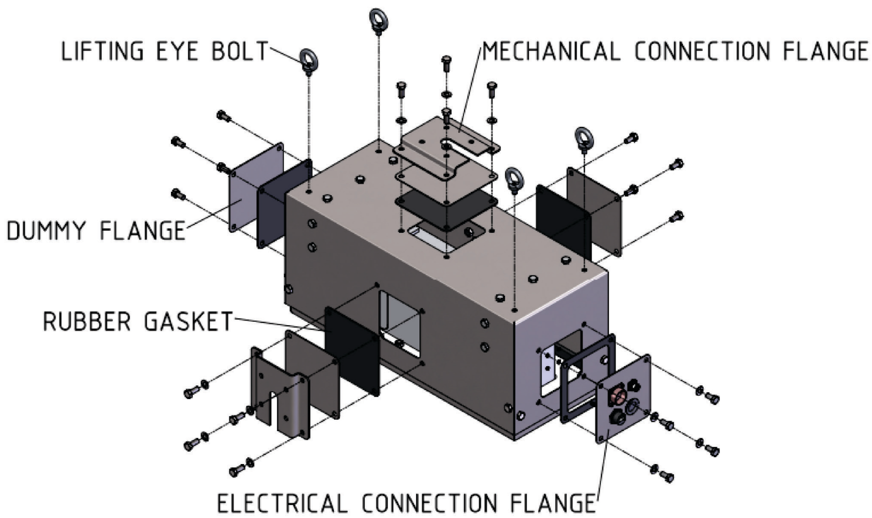


Figure 34: Universal connection interface

6.1.3 Cooling option

As described in subsection 5.3.6, the optional cooling system concept of the Imager Unit was tested using a liquid cooling module containing a TEC and a water block, shown in Figure 36. The cooling module is comprised of the water block on top of the module, the TEC housing in the middle surrounded by foam rubber insulation, and an aluminum block on the bottom. The maximum power rating of the cooling module is 265W, which far exceeds the required 29,30W cooling power as determined in subsection 5.3.1. Although a TEC cooling module with a power rating closer to the requirements could likely be obtained with a lower cost, the selected module was already being used in other Outotec products, making it readily available at an acceptable price point for the RockSense system. In order to avoid water condensation caused by low temperature points, the TECs inside the liquid cooling module were switched to the ones selected according to attachment 5. Thus the maximum cooling power of the liquid cooling module could be reduced from 265W to 30W. The same setup was also used in the cooling concept test (subsection 5.3.6) and its performance was known to be sufficient. Therefore, this liquid cooling module was selected to be used in the Imager Unit cooling system. The cooling system concept specifies the cooling module to be attached directly on the 3D imager’s surface.

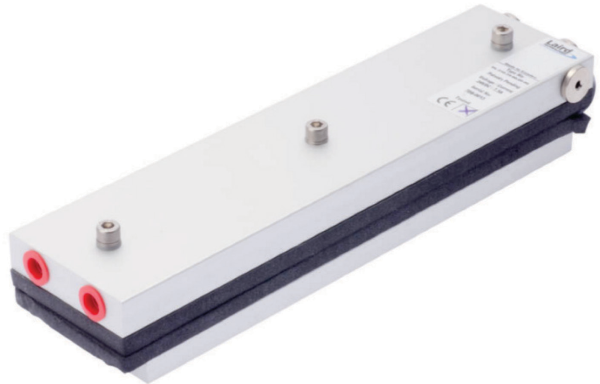


Figure 35: Liquid cooling module selected for the Imager Unit cooling system [26]

According to the manufacturer, the cooling module should be attached to the surface of the cooled component either via threaded holes in the bottom surface of the module, or by compressing the lower aluminum block of the module against the surface [27]. The former option was not considered viable in this case, since there was no way to create a bolt connection through the 3D imager's surface without a violation of warranty conditions. After some brainstorming and examining other Outotec products that use the same cooling module, a simple solution was formed that would utilize the threaded holes in the 3D imager's sides to attach the cooling module to the top surface of the imager. The solution uses a bent sheet metal plate that can be attached to the threaded holes and two thin rods that can be inserted under the foam rubber insulation above the bottom aluminum block of the cooling module. The cooling module's attachment system is illustrated in Figure 37.

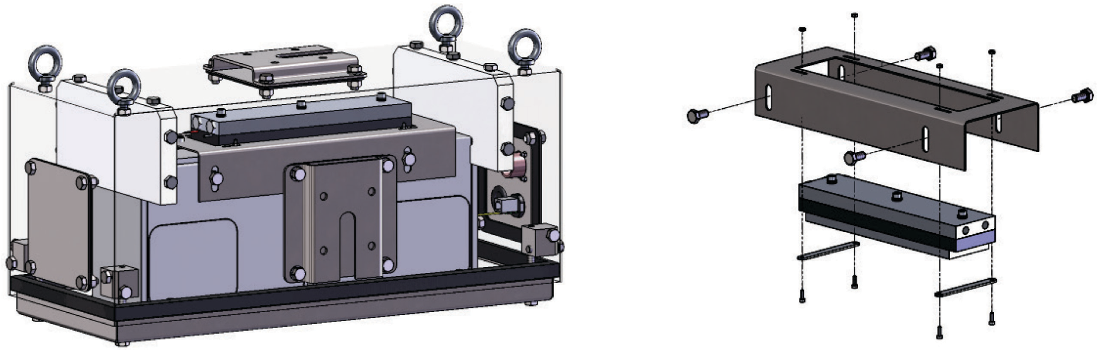


Figure 36: Liquid cooling module attachment system

The insulation required by the cooling system would be cut from 10 mm thick polyurethane foam sheets with an adhesive surface that could be glued to the inner walls of the enclosure. In order to prevent water from condensing inside the enclosure during cooling due to the pressure difference between the inside and outside of the enclosure, a pressure relief valve was added to the enclosure frame. The valve allows air to move in and out of the enclosure without jeopardizing the desired IP66 rating.

The cooling concept also requires a filtered enclosure that contains the pump and radiator required for the liquid circulation. The enclosure would be a simple rectangular frame with the vertical faces comprised of filter fabric. This would enable a large filter surface area, which is necessary in dusty environments, while keeping the pump and radiator protected from dust and dripping water. Laser cut and bent stainless steel sheet metal was seen as the logical choice for the filtered enclosure material. Since sheet metal components were already being acquired, additional ones could be obtained easily and cost effectively. In order to decrease shipping costs of the enclosure to the installation site, the assembly was constructed from flat components that could be packaged in a small space when the filtered enclosure is disassembled. Even though an IP-rating will not be applied for the filtered enclosure, cable throughputs and pipe connectors are used to ensure that the pump and radiator are protected from dust. Figure 38 illustrates the basic structure of the filtered enclosure.

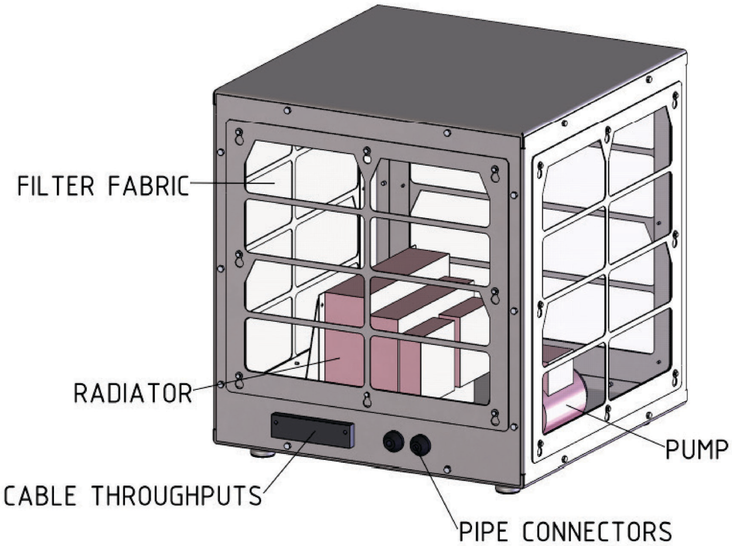


Figure 37: Filtered enclosure for cooling system pump and radiator

To compensate for changes in water density due to temperature fluctuations, an expansion tank is required for the closed liquid circulation. The expansion tank needs to be placed on the highest point of the liquid circulation system. It was considered likely that in many cases the Imager Unit would be located higher than the filtered enclosure. To accommodate these situations, an attachment flange was designed that allows the expansion tank to be installed directly on top of the Imager Unit, as seen in Figure 39.

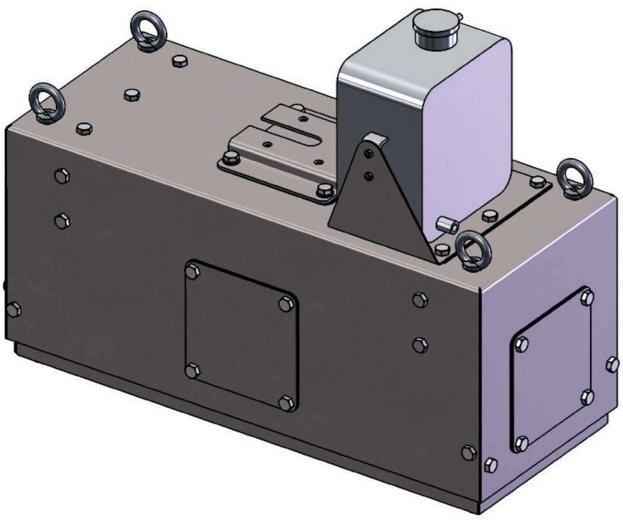


Figure 38: Expansion tank attachment to Imager Unit

6.1.4 Heating option

The requirements for the heater element include a small size, low price, and a convenient attachment method. Furthermore, the heater would preferably be operated with a 24V input voltage, since the same voltage is used by some other systems of the Imager Unit. As determined in subsection 5.4.2, at least 61,11 Watts of heating power is required. In order to avoid high temperatures that might be harmful to the equipment inside the enclosure and to ensure efficient heat dissipation, it was decided that two less powerful heaters would be used instead of one. After an investigation on commercial options for the resistive heating element, the component shown in Figure 40 was discovered. This heating element meets all the requirements for the heater and was readily available from a trusted vendor. With a 24V power source, two of these heating elements combined produce 80 Watts of heating power, which was considered suitable considering the heating power requirement and some additional redundancy.

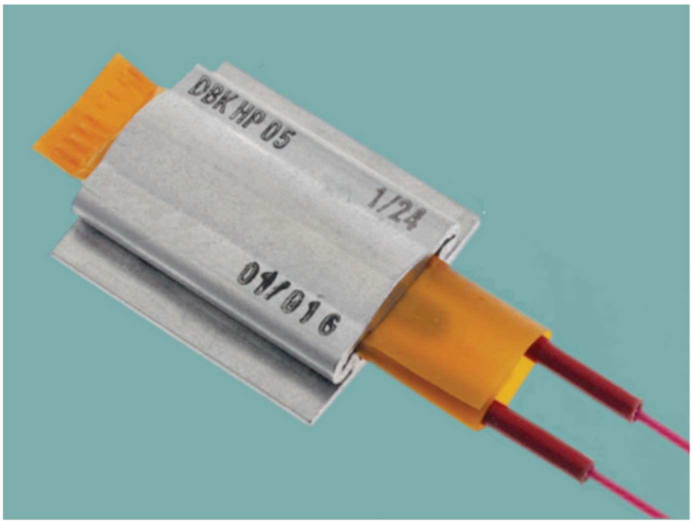


Figure 39: Resistive heater chosen for the Imager Unit heating system [28]

As with the cooling system, it was considered that attaching the heating elements directly to the 3D imager body would provide optimal thermal efficiency, since the heat would be transferred directly to the 3D imager. In order to aid the natural convection of the thermal energy, the heater should be positioned low inside the enclosure. A convenient way to achieve both design goals was to utilize the lowest of the three threaded holes in the imager's sides. A simple two piece sheet metal bracket, as shown in Figure 41, was designed to secure the heating element in place.

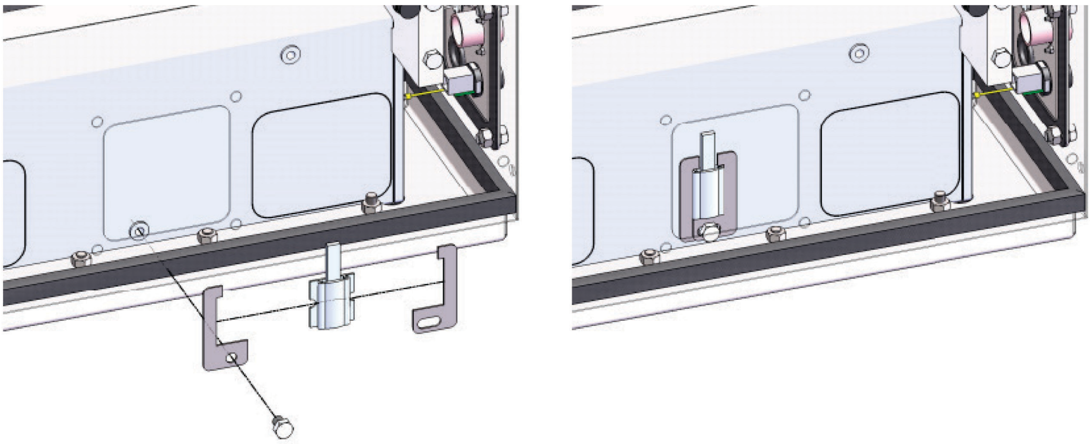


Figure 40: Heater element attachment mechanism

6.1.5 Video camera option

A commercial video camera was selected for the Imager Unit based on four criteria: physical size, operational environment, Power over Ethernet protocol, and low cost. The PoE protocol, which enables the camera to be operated using only a single network cable, is essential because there were no more wires available inside the 32-pin cable between the Imager Unit and the Control Cabin that could be used to transfer the operating current for the video camera. After an extensive investigation on available commercial options, a camera model that meets all the criteria was discovered, as seen in Figure 42.

Figure 41: Optional video camera chosen for the RockSense system

An inset for the camera was added to the bottom plastic part of the enclosure and an opening for the camera optics on the bottom plate. A sheet metal flange was designed, with which to attach the camera as seen in Figure 43. An O-ring was placed between the camera and the plastic part, in order to maintain protection from dust and water. An additional rubber gasket and a sealing flange were designed to be installed when the camera option is not used.

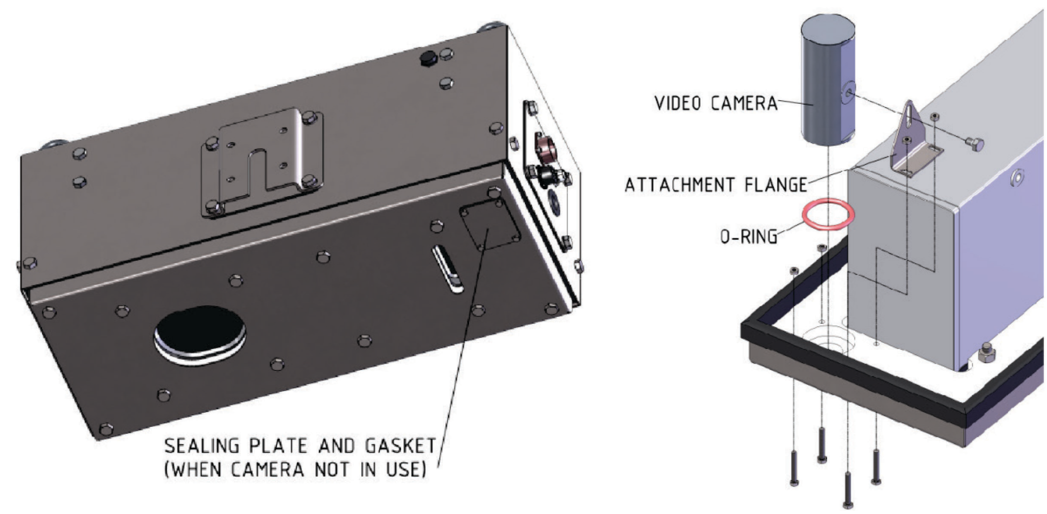


Figure 42: Optional video camera attachment system

6.1.6 Laser safety hatch

According to the laser safety standard SFS-EN 60825-1, a device with a class 3B laser must include a mechanical barrier that can be used to block the laser beam [29]. A simple latch was decided to be added in the bottom of the enclosure. After numerous design iterations, it was concluded that a simple metal plate would be placed into an inset machined into the bottom of the lower plastic plate part. The hatch could be locked in either an open or closed position by a threaded rivet installed in the hatch plate, a wing screw, and one of two insets in the plastic part. This mechanism allowed the laser hatch to be opened, closed, and secured in place without using any tools or having to detach and reattach any kind of fasteners. The laser safety hatch assembly is shown in Figure 44.

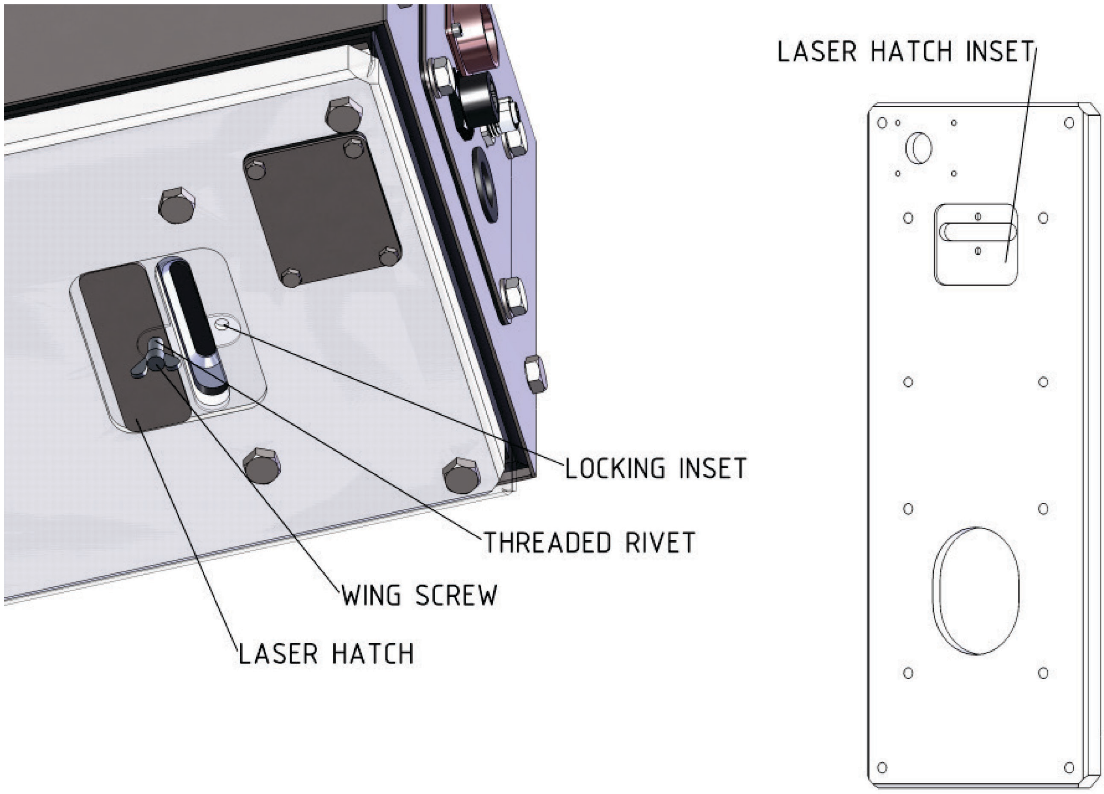


Figure 43: Laser safety hatch mechanism

6.2 Beta installation prototype

Having completed the CAD-model for the Imager Unit, the prototype could then be assembled. The beta installation site requires a cooling system, but the video camera option and the heating option were not required by the customer and therefore were left out of the first prototype. Although the finished product will have a full supply chain including subcontractors for every phase of manufacturing and assembly, the first prototype was assembled and partially manufactured by the product team themselves.

6.2.1 Acquiring components

Even though the commercial components for the finished product would be acquired by the company's procurement department, the parts for the first prototype were acquired by the project team and paid for directly from the project budget. All the laser cut sheet metal components were ordered from a single manufacturer, who would also bend, weld, and chemically polish the components.

A quotation for the plastic components was obtained from several manufacturers with CNC machining capabilities, but the cost and manufacturing times turned out to be too high to meet the project demands at that time. To save time and resources, the plastic parts were manufactured personally by the project team using the machining equipment at Aalto University's Mechatronics Innovation Lab. However, it was decided that the shape of the plastic parts should be redesigned for manufacturing during the design of the next prototype iteration. Because the video camera option would not be included in the beta installation, it was decided that the opening for the video camera would be left out of the bottom plastic part. Additionally, the bottom plastic part was seen to be excessively bulky so some of the unnecessary material was machined off from the part's edges. Figure 45 shows some of the completed sheet metal parts as well as the finished plastic parts.

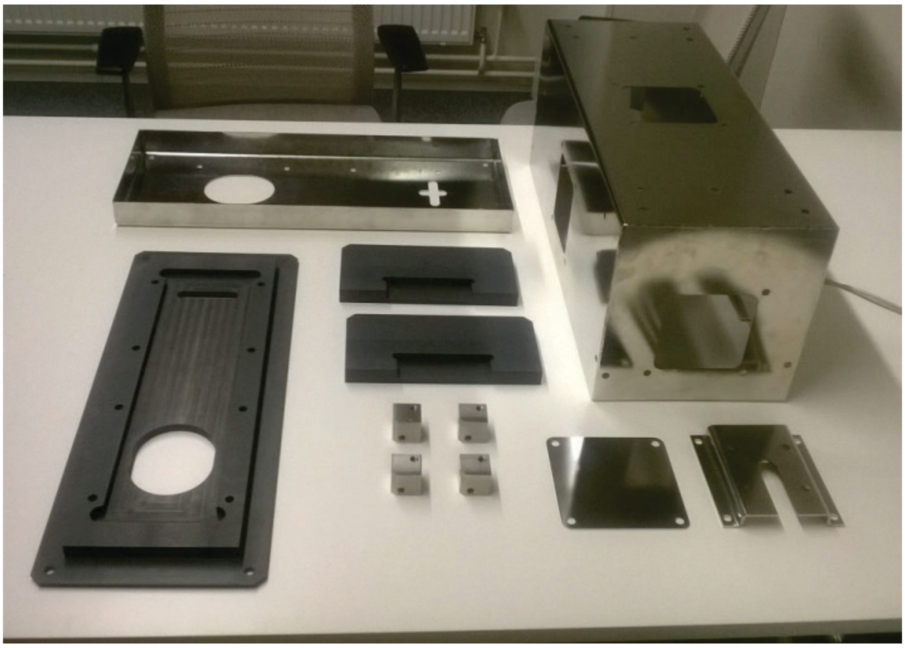


Figure 44: Finished plastic parts and some of the sheet metal components of the Imager Unit

6.2.2 Assembly

Assembling the prototype was carried out by the project team using Outotec's own facilities. It was thought that assembling the prototype personally would give the mechanical design team further insights into the product's mechanics and enable them to become aware of flaws in the design.

Indeed, some mechanical imperfections were noticed during the design phase of the Imager Unit. In order to achieve sufficient sealing for the enclosure to qualify for an IP66 rating, each bolt connection through the enclosure would need to be sealed. Rubber washers between the screw head and the enclosure were planned to be used for sealing the openings. However, as the screws were tightened, the rubber washers failed to stay properly in place due to the large compression force and their elastic behavior. If the rubber washer were to be partially pushed out from under the screw head, the sealing would be compromised. The problem is illustrated in Figure 46 taken during the prototype assembly. As a solution, it was decided that the rubber washers would be replaced by so called *USIT-rings*, which are essentially steel washers with an O-ring in the middle, as shown in Figure 47.

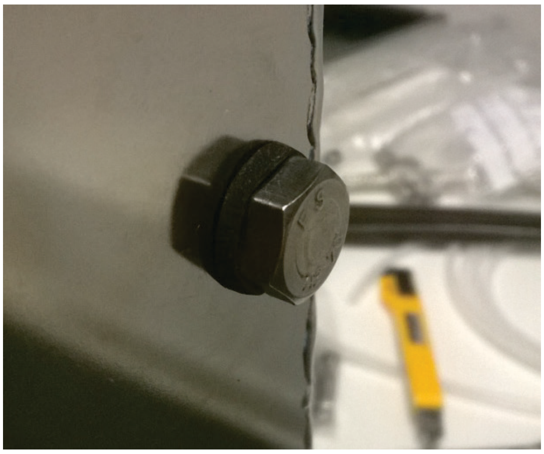


Figure 45: Rubber washer on the Imager unit enclosure

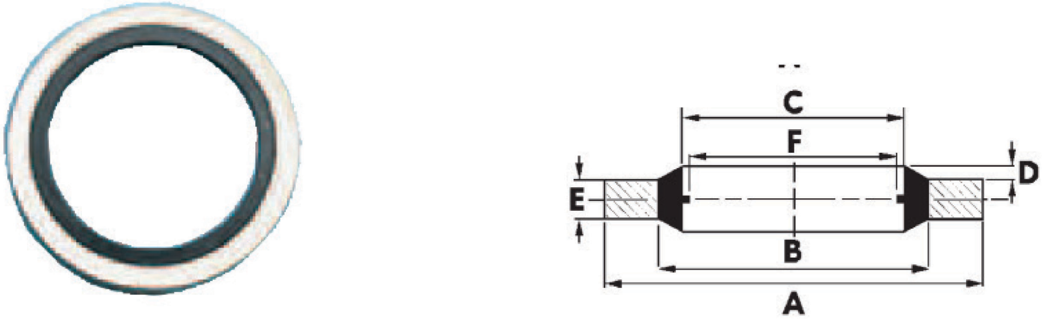


Figure 46: USIT-rings [30]

A more serious problem related to the enclosure sealing was discovered as the bottom plate was put in place. Due to inaccuracies in the enclosure frame manufacturing and inadequate design, the lateral force inflicted by the D-shaped rubber seal on the enclosure frame was so large that it caused the frame walls to curve outward as shown in Figure 48. Consequently, the sealing in the middle point of the enclosure, where the curve is at its widest was left unsatisfactory. The tightness of the bottom sealing also caused the attachment and detachment of the bottom plate to be extremely difficult and time consuming. It was concluded that the design would not reach the target value of 15 minutes set for the engineering metric “time to replace the 3D imager”.

Figure 47: Bent side face of the Imager Unit enclosure

Furthermore, the design of the bottom plate and the D-shaped sealing caused problems in the corners of the bottom plate as well. Despite significant efforts, the sealing material could not be cut in a way that would allow the corners to be completely sealed, as demonstrated in Figure 49.

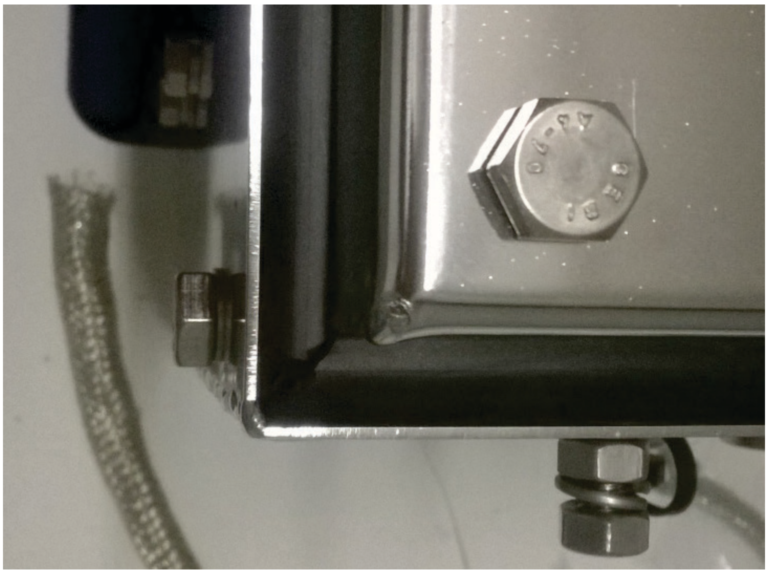


Figure 48: Bottom corner of the Imager Unit with unsatisfactory sealing

Changes to the bottom plate attachment and sealing structure would require significant modifications to the design and acquiring new parts from the manufacturer. Therefore, it was decided that the beta installation would use the current design and improvements would be made for the next design iteration.

Another design flaw was discovered on the universal connection interface. Since the flanges are attached to the enclosure frame by a screw and nut connection, changing the position of a flange would require removing the bottom plate to access the nuts inside the enclosure. This might cause problems in some sites for example if it is discovered that the intended mechanical connection will not work and a mechanical attachment flange needs to be moved from one face to another.

Because the cooling system would be included in the beta installation, one of the dummy flanges was modified to house the liquid input and output valves. The modification included simply drilling two holes on the flange and installing the quick release valves specified during the embodiment design phase. Another design error was, however, noticed as the liquid cooling module was being installed. The distance between one of the upper plastic parts and the cooling module was such that the plastic tubes going into the cooling module have to make a very steep turn. This raised concern about a possible blockage in the liquid circulation system caused by the liquid tube folding in an acute angle that could lead to overheating the 3D imager or even a rupture in the liquid circuit inside the enclosure. The problem was solved by reinforcing the liquid tube with a thicker, more rigid plastic tube near the cooling module. The rigid pipe would guide the tubes around the upper plastic parts in a gentler arch, preventing the thinner pipe from folding. However, a better system was decided to be designed for the second design iteration. The piping problem and the initial solution are demonstrated in Figure 50.

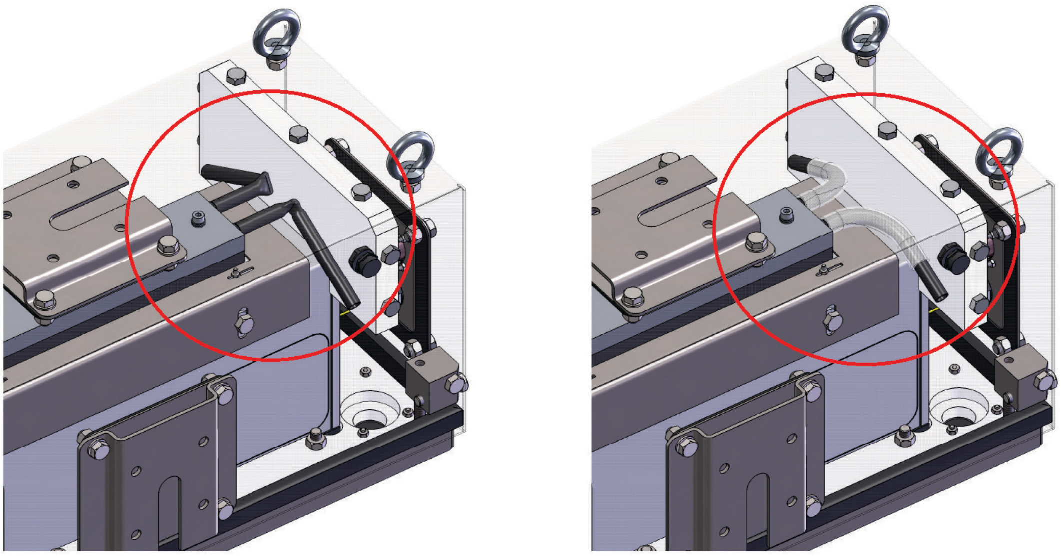


Figure 49: Liquid cooling module piping problem (left) and initial solution (right)

To reduce shipping costs, the filtered enclosure containing the pump and radiator for the cooling system was designed to be assembled at the installation site. However, for the beta installation it was decided that the enclosure would be assembled by the project team in order to uncover any potential design errors. The filtered enclosure containing the pump, radiator, and all the required pipe connectors and cable throughputs were assembled as seen in Figure 51.

Figure 50: Filtered enclosure of the cooling system (filter fabrics not yet attached)

After the Imager Unit and the filtered enclosure for the cooling system were successfully assembled, some final tests were conducted to ensure that the system works as intended. The wiring was tested to verify that all the electrical connections were made correctly and that the wires weren't damaged during assembly. The electronic systems were tested and it was confirmed that readings from the 3D imager and the thermometers could be obtained. The liquid circulation was also tested in order to verify that the pump works as intended and that there were no leakages or blockages in the system. During this process, it was discovered that carry handles on the Imager Unit would make the installation and maintenance procedures significantly easier. After verifying that the electronic systems and the liquid circulation worked as intended, the RockSense system was ready to be packaged and shipped to the beta installation site.

6.2.3 Installation

The prototype was packaged and shipped to the installation site in Mauritania, where a team of Outotec specialists would take care of the installation and setup of the RockSense system, along with some other Outotec products.

The conveyor belt, above which the Imager Unit would be installed, had a walking platform above it that could be used as a support structure. It was determined that the simplest attachment method in the given situation would be a cable attachment using the lifting eye bolts in the top corners of the enclosure, as shown in Figure 52.

Figure 51: Imager Unit attachment of the RockSense beta installation

The filtered enclosure and the Control Cabin would be installed on the platform above the belt. Since the filtered enclosure was placed higher than the Imager Unit, the expansion tank for the liquid circuit would be placed on top of the filtered enclosure, as seen in Figure 53.

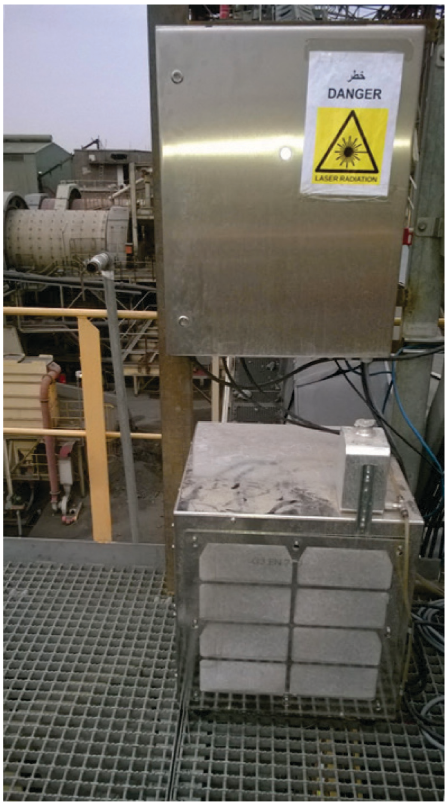


Figure 52: The filtered enclosure, expansion tank, and Control Cabin of the RockSense beta installation

No major design flaws were discovered during the installation phase that would require modifications to the existing mechanical design.

7 Feedback and iteration

The primary goal of the design work presented in this thesis was to design and build a working prototype for the RockSense system. As described in the previous chapters, the prototype was successfully designed, manufactured, assembled, and installed. However, as seen in chapter 5, the first prototype was not yet successful in meeting all the design criteria defined for the RockSense system. The secondary goal for this thesis is a successful productization of the 3D optical granulometry technology, which has not been achieved by the beta installation prototype.

As described by Pahl & Beitz [15], a product development project is typically an iterative process that requires frequent evaluation and improvement of existing designs. In order to reach the secondary goal of this thesis, the first prototype of the Imager Unit is to be reviewed and the design improved where necessary, in order to reach all the design criteria and engineering metrics targets defined in section 4.2. The following subsections describe the steps taken in the review and iteration process of the mechanical design of the RockSense system. The goal of this process is to produce a design that can be taken through the following decision gate of the RockSense project and finally to the product launch phase of the project.

7.1 Prototype performance

Although some design faults were already discovered during the assembly phase of the Imager Unit, performance of the beta installation prototype over a long time period would give far greater insights into whether or not the design works as intended in the actual operational environment. After the RockSense system beta installation had been operational for two months, initial performance feedback could be gathered.

Mechanically the system has worked as intended, although as discovered during the assembly phase, removing and reattaching the bottom plate for maintenance purposes was seen as too difficult and time consuming. However, there was some suspicion on whether the 20 mm wide circular steel pipe intended to be used with the mechanical attachment flanges would be sufficiently thick. If a long pipe was needed in some installation situations, the pipe might act as a spring and cause considerable oscillation of the Imager Unit due to vibration from the conveyor belt. Some concern was also raised by the 3D imager’s optics getting visibly dirty during operation, as seen in Figure 54.

Figure 53: 3D imager optics after short operation time at the beta installation site

However, any decline in the imager performance or laser intensity due to dust gathering on the imager optics was not discovered. A longer operation time would still be required in order to determine whether the dust would actually have a negative effect on the 3D imager's performance.

7.1.1 Engineering metrics review

In order to objectively review the prototype performance, the engineering metrics listed in Table 3 (section 4.2) would be measured and compared against the target values. Certain metrics, such as "standard maintenance interval" or "successful installations without modification" require a long time period for accurate measurement. Waiting for definitive results for these metrics before creating the next design iteration was not possible considering the RockSense project schedule. These metrics were evaluated based on expertise from the project team, and the maintenance engineer on the beta installation site. The metrics that could be measured were measured before shipping the prototype to the beta installation site. The results are presented in Table 5. The metrics that reached the target values are denoted by a green color. Red color represents a metric that failed to reach the target value, and a yellow color signifies that the value can only be determined after a longer test period, or in the case of the metric "Protection against intrusion", after the IP tests have been committed.

Table 5: Actual engineering metrics values of the beta installation prototype

Metric	Unit	Target value	Actual value	Relative weight (HOQ)	Comments
BOM cost	€	Confidential	Confidential	4,7	Actual value lower than target value
Total mass	kg	25	23	4,9	Measured with cooling system in place
External dimensions	mm	600x500x400	558x245x220	6,0	
Time to replace the 3D imager	min	15	30	2,9	
Operation time	%	95	TBD	12,2	Estimation: > 95%
Standard maintenance interval	months	6	TBD	9,3	Estimation: > 6 months
Maximum operational environment temperature	°C	55	> 55	7,4	
Minimum operational environment temperature	°C	-30	< -30	7,4	
Protection against intru-sion (dust, water etc.)	IP rating	IP66	TBD	8,4	Estimation: IP64
Successful installations without modification	%	80	TBD	21,0	Estimation: < 90%
Optional video camera installment	yes/no	yes	yes	3,5	
Standards SFS-EN 60825-4 and SFS-EN 12254 are met	yes/no	yes	yes	5,3	
Requires water input	yes/no	no	no	3,5	
Requires pressurized air input	yes/no	no	no	3,5	

The results show that the first prototype reached the target values in all except one metric that could be measured at the current time. One metric that could not be measured, was estimated not to reach the target value. According to this evaluation, the ability to protect against intrusion should be improved and the time to replace the 3D imager should be shortened. The unsatisfactory performance of both failed metrics is primarily caused by the bottom plate design of the enclosure and the way in which it was sealed.

7.1.2 Further development

In addition to the engineering metrics that did not meet the target values, room for improvement also existed for other aspects of the design. These design faults have been documented in the previous chapters and sections and are listed below for clarity:

Required improvements on the design:

- Removing and reattaching the enclosure bottom is too difficult and time consuming
- The bottom sealing of the enclosure is not sufficient for an IP66 rating
- The input and output pipes of the liquid cooling module must make too steep a turn to get around the upper plastic component of the enclosure, causing a risk of folding the tube
- The steel pipe interface on the mechanical attachment flanges is too narrow
- The connection flanges cannot be moved to another enclosure face without detaching the enclosure bottom
- The plastic components of the enclosure are too expensive to manufacture
- Carry handles should be added to the Imager Unit

7.2 Second design iteration

Based on the improvement requirements defined in the previous section, the second iteration of the Imager Unit could be designed. The goal of the new design was to meet all the design criteria defined for the RockSense system and reach all the target values for the engineering metrics. Furthermore, the new iteration will improve the design in terms of manufacturing costs, user-friendliness, and robustness. If the new design meets all of the RockSense product requirements, it could be taken to through the following decision gate of the project and on to the product launch stage.

7.2.1 Basic Structure

The design process was started by editing the bottom plate structure. The main problems that cause the poor sealing of the bottom and difficulties in removing and reattaching it are related to the sealing mechanism of the bottom plate. The sealing relies on careful dimensioning of the bottom plate and top frame of the enclosure, to ensure that the lateral force inflicted on the frame by the D-shaped seal is large enough for a proper seal but small enough that it will not cause the frame to bend. However, the bent sheet metal components are difficult to manufacture with sufficient tolerances for such a precise design. Furthermore, even if the dimensioning was perfect, the corners of the bottom plate would still be left with unsatisfactory sealing since the sealing material has to be cut in two separate pieces at the corners.

To fix the sealing problem, it was determined that a better and simpler sealing would be achieved by compressing two plates against each other, with a sealing gasket in between. A flat flange at a right angle could be added to the bottom edge of the top frame, against which a plate could be compressed. However, this type of sealing would conflict with the 3D imager attachment system, where the imager is compressed between the top frame and the bottom plate of the enclosure. If the imager attachment method was left unchanged, the bottom plate would be compressed against two separate sealing gaskets in different vertical levels. Slight inaccuracies in the dimensions of the sheet metal frame of the plastic parts could cause an insufficient seal on one of the gaskets, as shown in Figure 55.

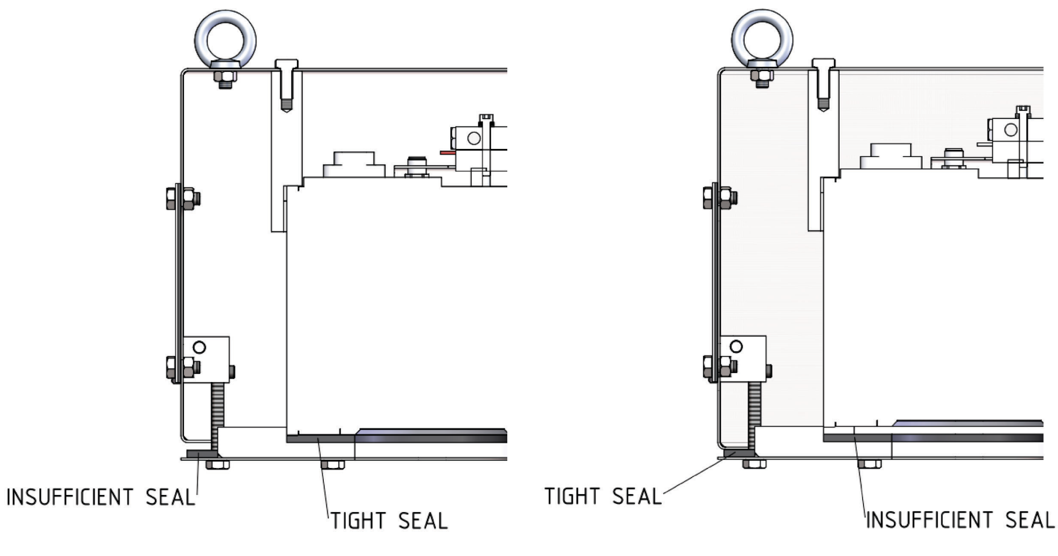


Figure 54: Potential problems with the new enclosure bottom sealing system (manufacturing inaccuracies accentuated)

This sealing problem could be managed with careful design and tight manufacturing tolerances but as mentioned above, tight tolerances are difficult to achieve with bent sheet metal components. Another solution would be to attach the imager unit directly to the bottom plate and thus remove the upper plastic parts completely. Removing the upper plastic parts would offer the additional benefits of solving the piping problem related to the cooling system as well as reducing the manufacturing costs and the weight of the assembly. A simple sheet metal flange was designed, as seen in Figure 56, which would be used to attach the 3D imager to the bottom plate via four threaded rods.

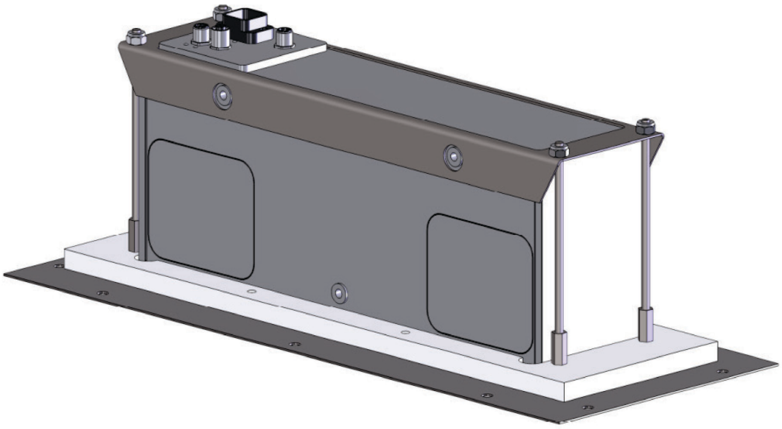


Figure 55: 3D imager attachment flange

After a reviewing a few design alternatives, it was decided that the bottom plate should be kept as a simple flat plate, with downward facing flanges on each edge. The flanges would provide structural stability and stiffness, and could potentially function as attachment points for a dust removal system in the future. Additionally, simple carry handle shapes could be added to the flanges from which the Imager Unit could be lifted up and carried during installation and maintenance procedures. Since nuts or screw heads cannot be accessed from inside the enclosure during the bottom plate attachment, welded bolts would be added to the bottom flanges of the top frame. The bottom plate could then be attached by simply inserting suitable nuts onto the welded bolts. After a discussion with the manufacturer of the sheet metal components, it was discovered that welded bolts could be installed easily and precisely by the same manufacturer with minor increases to manufacturing costs. Therefore, the bottom plastic parts were decided to also be attached to the bottom plate using welded bolts. Adding welded bolts would remove the necessity to create openings for a nut and bolt connection, improving the sealing of the bottom structure. The new bottom plate assembly can be seen in Figure 57.

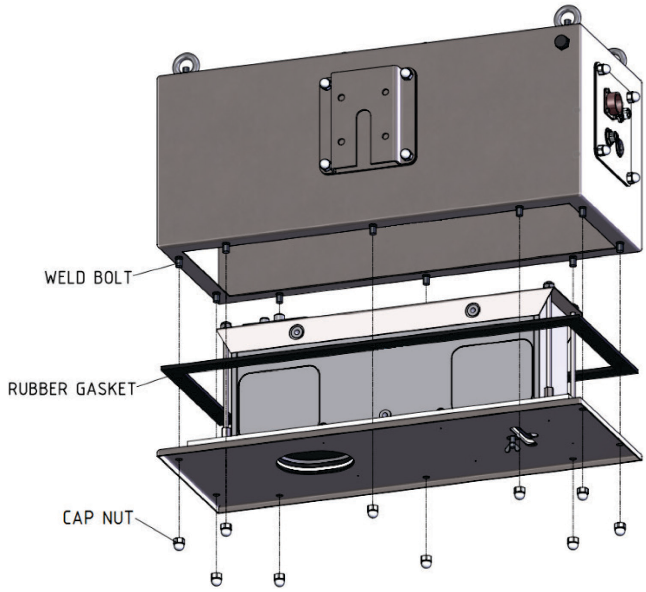


Figure 56: The new Imager Unit bottom plate assembly

7.2.2 Mechanical Connection Interface

According to the improvement requirements on the Imager Unit design, the steel pipe interface on the mechanical attachment flanges was considered too narrow. Therefore, the width of the flange was increased 20 mm in the vertical and lateral directions in order to accommodate increasing the steel pipe interface from 20 to 40 mm. The nut and screw connections that attach the flanges to the enclosure frame were replaced with welded bots so that they could be removed and reattached without having to remove the enclosure bottom while removing openings from the frame and improving the enclosure sealing. The lifting eye bolts on the top corners of the enclosure were also replaced by lifting eye nuts connected to welded bolts. Furthermore, removing the upper plastic parts from inside the enclosure meant that the flanges could be moved upwards close to the upper face of the enclosure frame. This would provide a more direct transmission of force along the frame and reduce material deformation when the mechanical attachment flanges are used. The new mechanical connection interface design is shown in Figure 58.

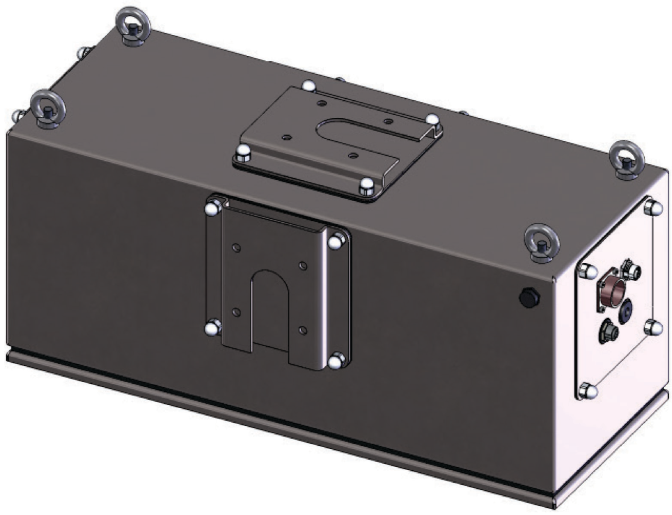


Figure 57: Second design iteration of the mechanical connection

7.2.3 Manufacturing Costs

Removing the upper plastic components significantly decreased the manufacturing costs related to the Imager Unit. However, the lower plastic part was still considered too expensive. The initial design required machining from multiple sides of the part using different tool sizes, which caused the CNC programming and machining of the part to be time consuming and expensive. The new bottom plate structure allowed the size of the part to be decreased significantly. In order to remove excess weight, the plate thickness was changed from 20 to 15 mm. The chamfers in each bottom edge could also be removed since the part was no longer attached to the walls of the bottom plate, where the bending radius would need to be considered. An idea emerged that the inset for the laser safety hatch could be replaced by adding another rubber gasket under the plastic part, to which the inset shape could be cut. This would also increase the bottom sealing, since no water or dust could enter the enclosure from between the bottom plate and the plastic part. The small insets, to which the laser hatch could be secured, could be drilled through the plastic part, since the sealing gasket between the 3D imager and the plastic part would prevent dust or water from entering the enclosure through them. The new bottom plastic part design, as seen in Figure 59, could be machined from only one side with substantially shorter machining and programming times than the initial component.

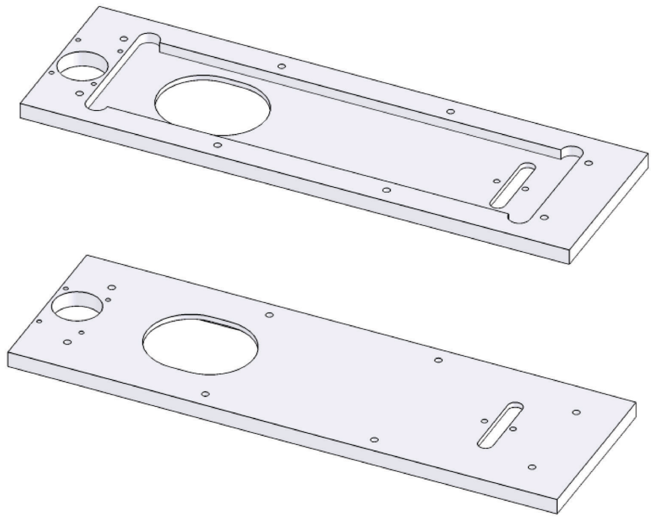


Figure 58: Second iteration of the bottom plastic part

7.2.4 Design review

Due to time restrictions, the second design iteration could not be manufactured during the making of this thesis. Therefore, explicit measurements of its performance could not be obtained. However, experiences from the initial design, and virtual measurements from the CAD-model allowed the project team to make good estimations about the performance of the second design iteration on the engineering metrics. The estimations of these metrics are presented in Table 6.

Table 6: Estimated values of the engineering metrics for the second design iteration

Metric	Unit	Target value	Estimated value	Relative weight (HOQ)	Comments
BOM cost	€	Confidential	Confidential	4,7	Actual value lower than target value
Total mass	kg	25	23	4,9	Virtual measurement from CAD-model, with optional subsystems
External dimensions	mm	600x500x400	558x245x220	6,0	Virtual measurement from CAD-model
Time to replace the 3D imager	Min	15	15	2,9	
Operation time	%	95	>95	12,2	
Standard maintenance interval	Months	6	6	9,3	
Maximum operational environment temperature	°C	55	> 55	7,4	
Minimum operational environment temperature	°C	-30	< -30	7,4	
Protection against intrusion (dust, water, etc.)	IP rating	IP66	IP66	8,4	
Successful installations without modification	%	80	90	21,0	
Optional video camera installment	yes/no	yes	yes	3,5	
Standards SFS-EN 60825-4 and SFS-EN 12254 are met	yes/no	yes	yes	5,3	
Requires water input	yes/no	no	no	3,5	
Requires pressurized air input	yes/no	no	no	3,5	

Table 6 shows that according to the estimations, the new design reaches all target values for the engineering metrics, and therefore meets all the customer needs and product requirements. However, before the engineering metrics can be explicitly reviewed by actual measurements from a physical prototype, the performance of the new design cannot be definitively verified.

8 Summary

This thesis contributes to the development process of an entirely novel ore size analysis system by the name of RockSense. The RockSense system analyzes granular material, particularly crushed ore, from a moving conveyor belt using a 3D imager and complex algorithms that determine the size distribution of the material. The RockSense system differentiates from its competition by being the first commercial system in the field to utilize 3D optical granulometry technology, and by providing a larger operational environment than the competition. This thesis was commissioned by Outotec with the intention of producing the mechanical structure of the product and advancing the project from its conceptual design phase to product launch. The RockSense system is intended for optimizing the efficiency of various processes within the mining, mineral, and metal industry (MMMI), and particularly ore grinding processes. Although the motivations behind the RockSense project are primarily financial, the project contributes to decreasing the ecological footprint of the MMMI by enabling more efficient process control and reducing wasted energy.

The prior work done on the RockSense project included a detailed business analysis and conceptual design. The conceptual design, however, was related mainly to software aspects of the project and little work had gone into mechanical design. The mechanical structure was divided into an Imager Unit, containing the 3D imager and all necessary subsystems to enable its operation, and a Control Cabinet that acts as a mediator between the Imager Unit and the control server. The Control Cabinet mechanics had been defined already during concept development. A detailed product requirement list had been composed, although it was determined insufficient in defining explicit boundary conditions for the Imager Unit's mechanical design during this thesis.

A systematic approach to the product development process was derived from engineering design literature. The systematic method presented by Pahl & Beitz [15] was selected as the primary guideline behind design decisions. Additional literature, namely Ulrich & Eppinger [20] was used to supplement the methodology when needed. User needs statements and explicit engineering metrics with target values were defined based on the initial requirement list to be used as boundary conditions for the mechanical design. In order to make the complex design problem more comprehensible, the problem was deconstructed into more manageable subfunctions. Conceptual solutions for each subfunction were found and evaluated. The most suitable concepts were combined to create the overall conceptual solution for the Imager Unit.

An iterative design approach was used in creating a complete CAD-model for the Imager Unit. Each proprietary component was defined in terms of manufacturing, assembly, compatibility, and other design aspects. A complete supply chain was defined for the product and a prototype built based on the design. The prototype was tested and evaluated based on the engineering metrics. The initial Imager Unit prototype did not reach all the target values for the engineering metrics. Particularly the enclosure compactness and the time to replace the 3D imager were unsatisfactory due to inadequate design of the bottom sealing mechanism of the Imager Unit enclosure. A second iteration of the design was made based on experiences from the prototype. According to evaluations by the project team, the second iteration would reach all the target values for the engineering metrics, although a physical prototype could not be built during the making of this thesis due to time constraints.

Even though the performance of the second design iteration of the Imager Unit cannot be explicitly verified without a physical prototype, the experiences from the first prototype and the expertise gained during the product development process allowed the project team to make a good estimation on the performance of the new design. Based on this estimation, the mechanical design process can be deemed successful based on the project goals and product requirements. The work related to this thesis will continue by verifying the new design with physical measurements on a new prototype. If the verification proves successful, the RockSense product can be taken to market and sold to mineral concentration plants and other operators in the MMMI worldwide. According to customer feedback and product performance, further design iterations can be made and the product improved on for the duration of its lifecycle.

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Attachments

Attachment 1. Relevant requirements from the initial RockSense requirement list. 2 pages.
Attachment 2. House of Quality Matrix. 1 page.
Attachment 3. Pairwise comparison of cooling system requirements. 1 page.
Attachment 4. Cooling concept evaluation matrix. 1 page.
Attachment 5. Thermoelectric cooler selection chart. 1 page.

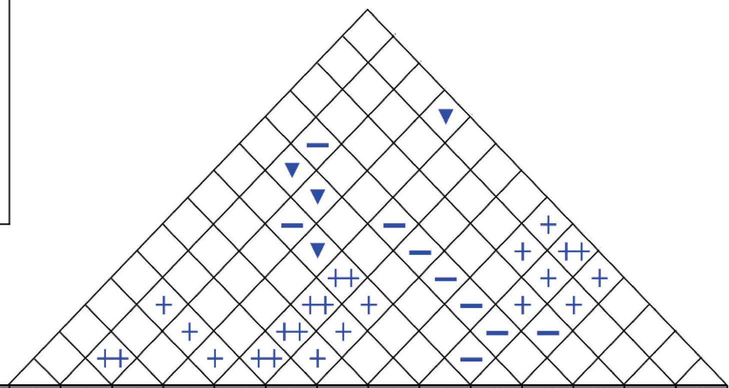
Attachment 1. Relevant requirements from the initial RockSense product requirement list

Category (ID)	Sub-Category	Description	Priority
BR	Cost	Max BOM cost (Classified)	MANDATORY
PC	Standards	No danger of eye damage can exist while the device is operational, i.e. the laser must be protected according to e.g. the standards SFS-EN 60825-1 and SFS-EN 12254.	MANDATORY
PC	Design	The external appearance must fit Outotec's brand	MANDATORY
UR	Operation	The position of the 3D imager must be adjustable easily and without causing a production stoppage (in both vertical and horizontal directions)	MANDATORY
UR	Installation	Equipment is easy to move to the site: size, weight, handgrips, packing etc.	MANDATORY
UR	Installation	The assembly of the camera unit is easy to intall electrically and mechanically to the supporting structure of the conveyor belt.	MANDATORY
UR	Installation	Devices can be installed without stopping the production.	MANDATORY
UR	Installation	The assembly of the camera unit is easy to install to differently sized supporting structures.	MANDATORY
UR	Operation	The amount necessary personal safety equipment is minimised.	NICE TO HAVE
UR	Operation	Detaching the camera from the cabinet, as well as maintenance of the cabinet, can be carried out from one side of the belt.	MANDATORY
UR	Operation	The protective layers of the camera lens must be capable of being cleaned from the outside of the cabinet.	MANDATORY
ER	Operation	Operating temperature range -30....+55 Celcius degree	MANDATORY
ER	Ambient	Storage temperature range 0....+70 Celsius degree	MANDATORY
ER	Ambient	Relative humidity < 85%	MANDATORY
ER	Ambient	Tolerate for 58 - 158 Hz / 5G vibration	MANDATORY
ER	Ambient	Noise level produced by RockSense <75dBA	MANDATORY
ER	Ambient	Compactness IP66 / NEMA 4X	MANDATORY
ER	Ambient	Tolerant to the dust: Dust gathering in the lens of camera or laser is prevented.	MANDATORY
ER	Installation	The maximum installation angle (to the horizontal, in the direction of the belt) of the support structure < 30 degree	MANDATORY
ER	Installation	Maximum measurement width (height 1280 mm) (Ruler E1200 (HB)) < 1550 mm	MANDATORY
ER	Installation	Minimum measurement width (height 280 mm) (Ruler E1200 (HB)) 500mm	MANDATORY
TR	Ambient	The system can be versioned according to the effect of the temperature or dust of the environment	NICE TO HAVE

TR	Ambi-ent	The camera unit is tolerant for an external vibration: vibration is not allowed to cause errors to the measurement	MANDA-TORY
TR	Design	The equipment consists of a camera, a camera cabinet, a field cabinet for accessories and attachments, a PC and the software necessary for operating, monitoring and controlling the system and for alerts.	MANDA-TORY
TR	Design	The support sturcture can be installed either facing towards or away from the direction of movement of the conveyor belt.	MANDA-TORY
TR	Opera-tion	The equipment optionally consists of the CCD-camera that pro-vides live image and an additional data for the analysis	OP-TIONAL
TR	Opera-tion	Must be able to measure the speed of the conveyor belt by using a pulse encoder	MANDA-TORY

Attachment 2. The House of Quality matrix

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	BOM cost	Total mass	External dimensions	Time to replace the 3D imager	Operation time	Standard maintenance interval	Maximum operational environment temperature	Minimum operational environment temperature	Protection against intrusion (dust, water etc.)	Installations possible witout modification	Optional video camera installment	Standards SFS-EN 60825-4 and SFS-EN 12254 are met	Requires water input	Requires pressurized air input
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	▲	▲	▲	▲	▲	▲	x	x	x	x
1	9	7,7	8,0	The Imager Unit is priced similarly to competitive 2D imagers	Θ													
2	9	4,8	5,0	The Imager Unit can be carried to the installation location without addi-tional equipment (e.g. forklift)		Θ								O				
3	9	5,8	6,0	The Imager Unit does not take up a lot of space at the installation site			Θ							O				
4	9	4,8	5,0	The Imager Unit enables replacing the 3D camera quickly and easily				Θ	▲				O					
5	9	2,9	3,0	The Imager Unit optics can be cleaned without having to open it						O			Θ					
6	3	4,8	5,0	The Imager Unit can be taken down for maintenance without causing a production stoppage					O					O				
7	3	4,8	5,0	The Imager Unit can be installed without causing a production stoppage					O					O				
8	9	5,8	6,0	The Imager Unit can be installed without special equipment or expertise					O					Θ				
9	9	5,8	6,0	The Imager Unit requires infrequent maintenance/can go long periods without maintenance					Θ	Θ	▲	▲	▲					
10	9	8,7	9,0	The Imager Unit is robust against dust, humidity and extreme temperatures					Θ	Θ	Θ	Θ	Θ					
11	9	9,6	10,0	The Imager Unit can be installed above conveyor belts with varying support and cover structures		O	O							Θ				
12	9	5,8	6,0	The Imager Unit does not require a water supply										O			Θ	
13	9	5,8	6,0	The Imager Unit does not require a pressurized air supply										O				Θ
14	9	8,7	9,0	The Imager Unit can be customized according to customer's special needs			▲				O	O		Θ				
15	9	5,8	6,0	The Imager Unit enables video surveillance for additional information and feedback.											Θ			
16	9	8,7	9,0	The Imager Unit does not expose personnel to the risk of eye damage												Θ		
				Target or Limit Value	Confidential	25kg	600x500x400mm	15min	95 %	6 months	55°C	-30°C	IP66	80 %	yes	yes	no	no
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	3	5	3	7	3	5	7	1	5	7	1	3	3	4
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9
				Weight / Importance	69,2	72,1	89,4	43,3	180,8	138,5	109,6	109,6	124,0	311,5	51,9	77,9	51,9	51,9
				Relative Weight	4,7	4,9	6,0	2,9	12,2	9,3	7,4	7,4	8,4	21,0	3,5	5,3	3,5	3,5

Attachment 3. Pairwise comparison of the cooling system requirements

Objectives	Low costs	Low maintenance requirements	Small and lightweight (in camera box)	Easy installability and maintenance	Minimal disturbance to other functions	Robust against dust, vibration etc.	Min storage temperature (below 0C)	Max operating temperature over 55C	Large cooling power range	Energy efficiency	Expected lifetime	Adjustable cooling power	Overall compactness (no field cabinets etc.)	Applicable to other products	Simplicity (mechanical, electrical etc.)	SUM
Low costs	-	0	1	1	1	0	0	1	1	1	1	1	1	1	1	11
Low maintenance requirements	1	-	1	1	1	0	0	1	1	1	1	1	1	1	1	12
Small and lightweight (in camera box)	0	0	-	0	1	0	0	1	1	1	0	1	1	1	1	8
Easy installability and maintenance	0	0	1	-	0	0	0	1	1	1	1	1	1	1	1	9
Minimal disturbance to other functions	0	0	0	1	-	0	0	1	1	1	1	1	0	1	0	7
Robust against dust, vibration etc.	1	1	1	1	1	-	0	1	1	1	1	1	1	1	1	13
Min storage temperature (below 0C)	1	1	1	1	1	1	-	1	1	1	1	1	1	1	1	14
Max operating temperature over 55C	0	0	0	0	0	0	0	-	1	0	0	1	0	0	0	2
Large cooling power range	0	0	0	0	0	0	0	0	-	0	0	1	0	0	0	1
Energy efficiency	0	0	0	0	0	0	0	1	1	-	0	1	0	0	0	3
Expected lifetime	0	0	1	0	0	0	0	1	1	1	-	1	1	1	1	8
Adjustable cooling power	0	0	0	0	0	0	0	0	0	0	0	-	0	0	0	0
Overall compactness (no field cabinets etc.)	0	0	0	0	1	0	0	1	1	1	0	1	-	0	0	5
Applicable to other products	0	0	0	0	0	0	0	1	1	1	0	1	1	-	0	5
Simplicity (mechanical, electrical etc.)	0	0	0	0	1	0	0	1	1	1	0	1	1	1	-	7

Attachment 4. Cooling concept evaluation matrix

	Weight coefficient	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8
Low costs	0,105	5	6	9	2	5	3	5	6
Low maintenance requirements	0,114	5	9	9	4	5	5	5	7
Small and lightweight (in camera box)	0,086	7	7	3	6	4	6	6	8
Easy installability and maintenance	0,095	4	7	8	5	5	5	5	5
Minimal disturbance to other functions	0,067	6	7	9	6	5	6	5	6
Robust against dust, vibration etc.	0,124	6	8	9	5	5	6	5	6
Min storage temperature (below 0C)	0,133	7	8	9	6	7	7	6	7
Max operating temperature over 55C	0,019	6	6	3	8	6	7	6	6
Large cooling power range	0,010	5	5	4	8	6	7	5	5
Energy efficiency	0,057	6	7	4	7	7	6	4	5
Expected lifetime	0,076	6	7	7	6	6	6	5	7
Adjustable cooling power	0,000	8	7	6	7	6	6	5	6
Overall compactness (no field cabinets etc.)	0,038	5	8	7	3	5	3	4	4
Applicable to other products	0,029	6	7	7	4	5	5	6	5
Simplicity (mechanical, electrical etc.)	0,048	6	8	8	5	5	5	6	6
	Total score	5,789	7,413	7,610	5,011	5,411	5,269	5,317	6,109
	Rank	4	2	1	8	5	7	6	3

Attachment 5. Thermoelectric cooler selection matrix

TEC element	Operating current I (A)	Operating voltage V (Ohm)	Heat flow Q (W)	Temperature difference ΔT (°C)	Power consumption P (W)	Coefficient of performance
Marlow RC12-8 (Th=50°C)	8	16.4	25	49	131.2	0.191
Multicomp MCHPE-288-14-06-E (Th=50°C)	7	21	35	51	147	0.238
Laird CP2,127,06, (Th=50°C)	8.6	10.5	30	50	90.3	0.332
2 x Laird CP2,127,06 (Th=50°C)	6.7	9	15	50	120.6	0.249
TeTech HP-199-1.4-0.8 (Th=70°C)	5.6	16.3	30	50	91.3	0.329
2 x TeTech HP-199-1.4-0.8 (Th=70°C)	4.4	10.3	15	50	90.6	0.331
2 x TeTech VT-127-1.4-1.5-72 (Th=70°C)	3.2	10.8	15	50	69.1	0.434
2X Laird CP14,127,045 (Th=25°C)	6.9	11.7	15	50	161.5	0.186
2x Marlow RC12-8 (Th=50°C)	4.7	11	15	50	103.4	0.290
2x Laird ZT6,12,F1,4040 (Th=25°C)	4.5	11.4	15	50	102.6	0.292
2x Laird UT6,24,F1,5555 (Th=25°C)	4.6	24	30	50	110.4	0.272
TeTech VT-199-1.4-1.5 (Th=70°C)	4.2	20	30	50	84	0.357
2 x TeTech VT-199-1.4-1.5 (Th=70°C)	2.8	14.6	15	50	81.8	0.367
APH-161-12-14-E (Th=75°C)	4.00	20	30	50	80	0.375
2x APH-161-12-14-E (Th=75°C)	2.10	12	15	50	25.2	0.595
3x APH-161-12-14-E (Th=75°C)	1.90	10.8	10	50	20.52	0.487
4x APH-161-12-14-E (Th=75°C)	1.80	10	7.5	50	18	0.417
2x APH-161-12-16-E (Th=75°C)	**2.00**	**12.5**	**15**	**50**	**25**	**0.600**
2x APH-161-12-18-E (Th=75°C)	2.00	14.8	15	50	29.6	0.507
3x APH-161-12-18-E (Th=75°C)	1.50	12	10	50	18	0.556
APH-199-14-08-E (Th=75°C)	4.00	14	30	50	56	0.536
2x APH-199-14-15-E (Th=75°C)	2.10	13	15	50	27.3	0.549
APH-241-10-08-E (Th=75°C)	2.80	18	30	50	50.4	0.595
APH-241-14-11-E (Th=75°C)	3.25	17.5	30	50	56.9	0.527